

# Status of the

**MIPP**



# Data Analyses

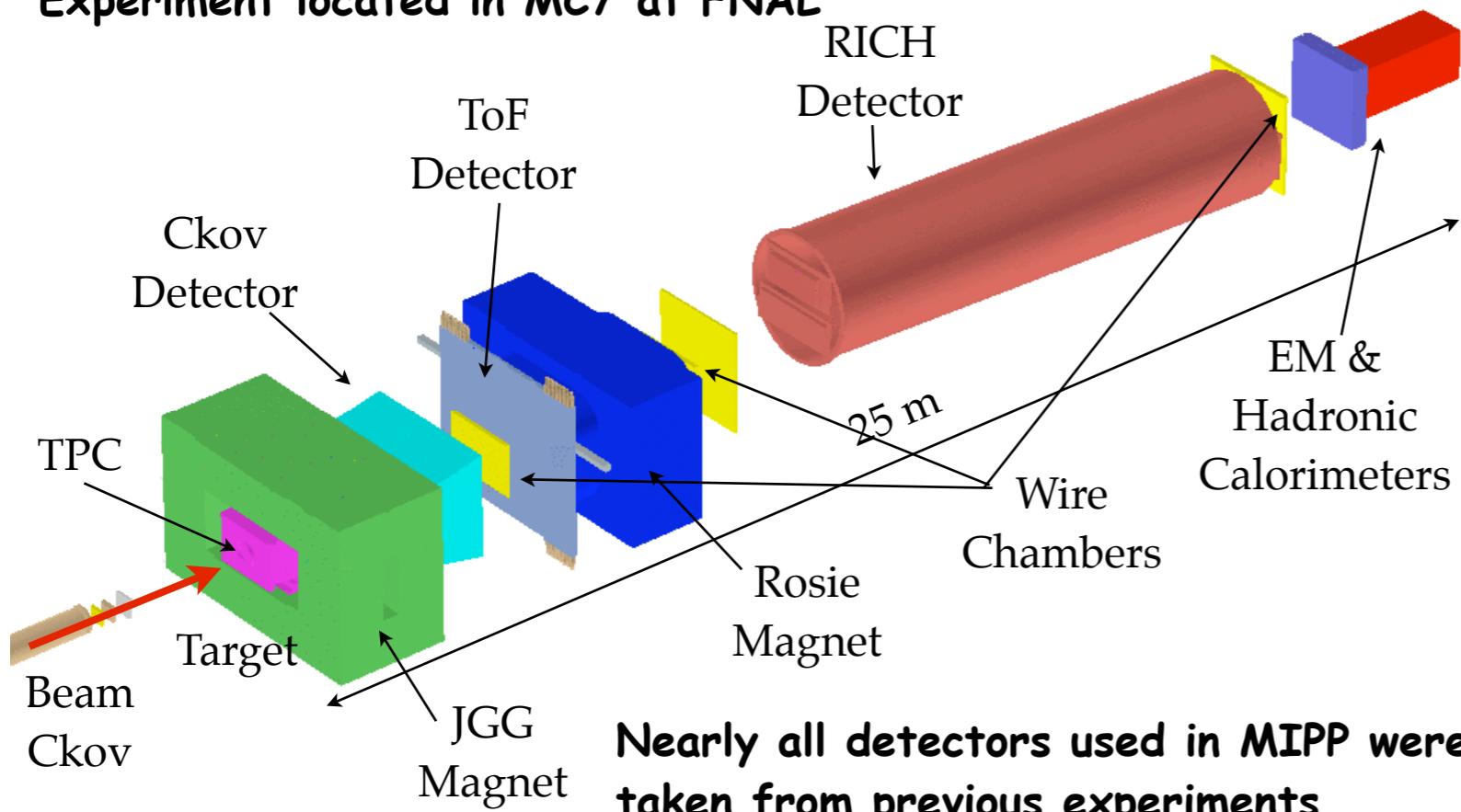
Jonathan M. Paley, Ph.D.

Indiana University

MTest/MIPP Upgrade Review - October 9, 2009

# Main Injector Particle Production (MIPP) Experiment

Experiment located in MC7 at FNAL



- Goal: collect comprehensive hadron production cross-section data set with particle id using various beams and targets (thick and thin).

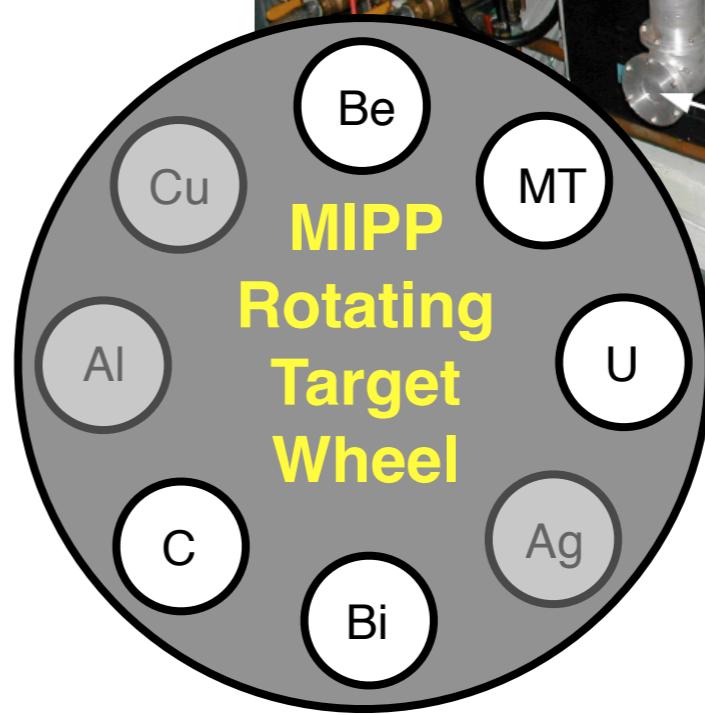
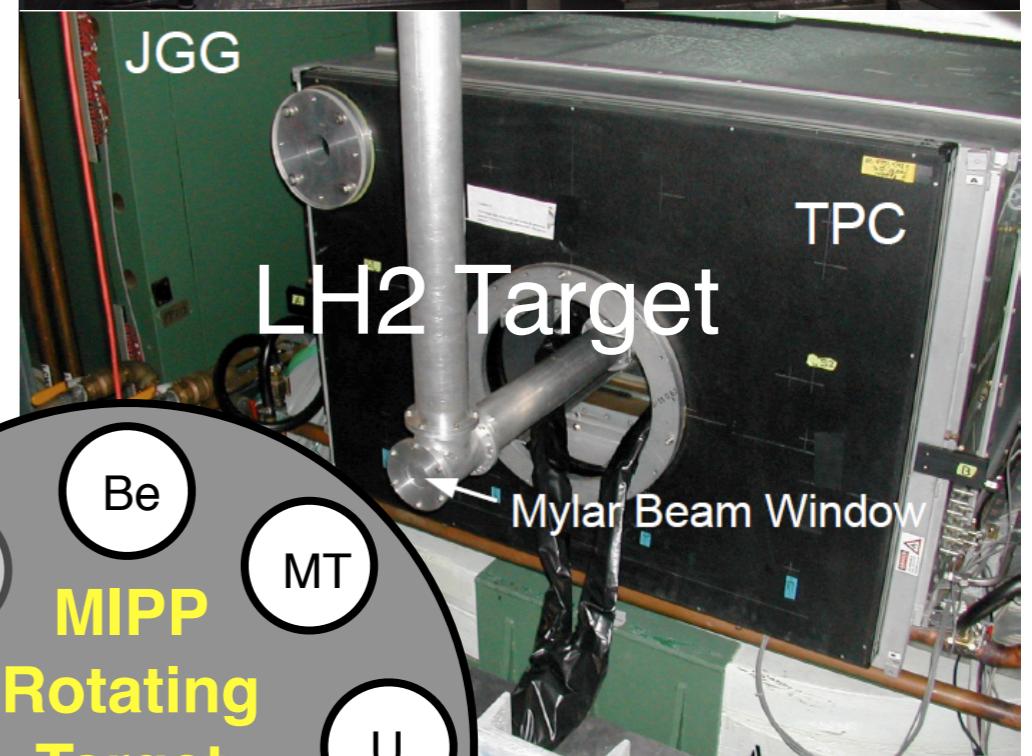
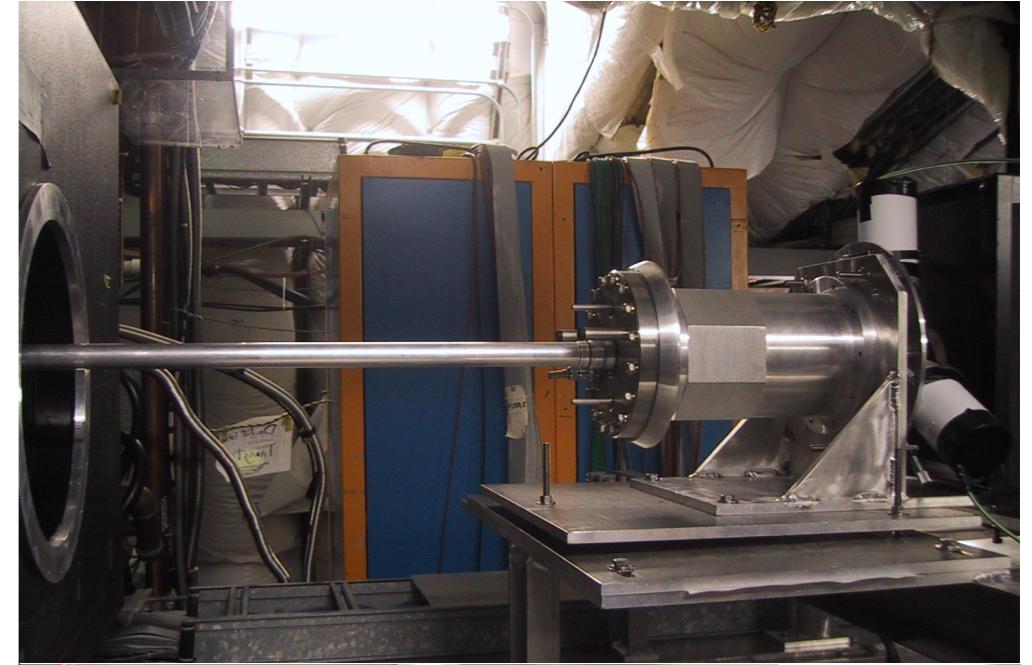
- Full acceptance spectrometer
  - Two analysis magnets deflect in opposite directions
  - TPC + 4 Drift Chambers + 2 PWCS

- Designed for excellent particle ID (PID) separation ( $2-3\sigma$ )



# The 2005-06 Data Run

- MIPP began its physics run in December 2004 and ran until February 2006.
- DAQ rate was  $\sim 25$  Hz, with MIPP receiving  $\sim 5\%$  of MI beam.
- Data collected:
  - $\sim 1.6 \times 10^6$  events of Main Injector 120 GeV/c protons on a spare NuMI target.
  - $\sim 3.2 \times 10^6$   $\pi$ 's, K's and p's at 120, 60, 35 and 20 GeV/c on 1-2%  $\lambda_L$  C and Be targets.
    - $\sim 7 \times 10^6$   $\pi$ 's, K's and p's at 85, 60, 20 and 5 GeV/c on 1%  $\lambda_L$  LH2 target.
    - $\sim 4 \times 10^6$   $\pi$ 's, K's and p's at 35, 60 and 120 GeV/c on Bi and U targets.



# MIPP Data Analyses

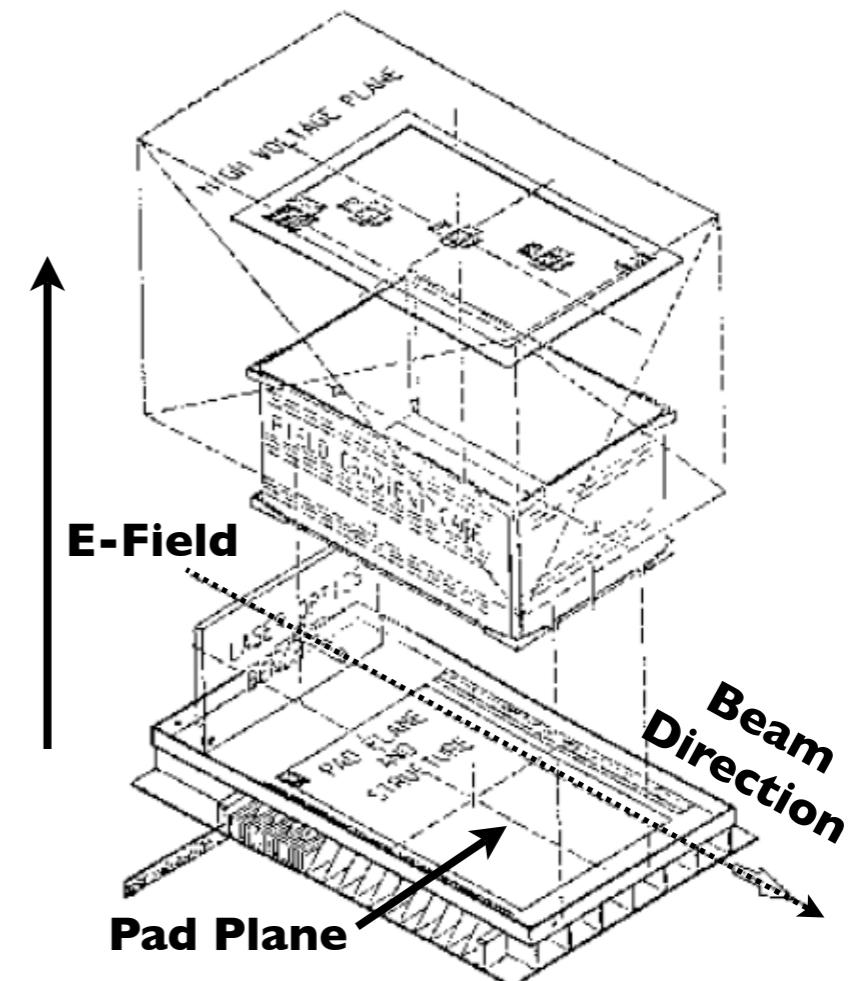
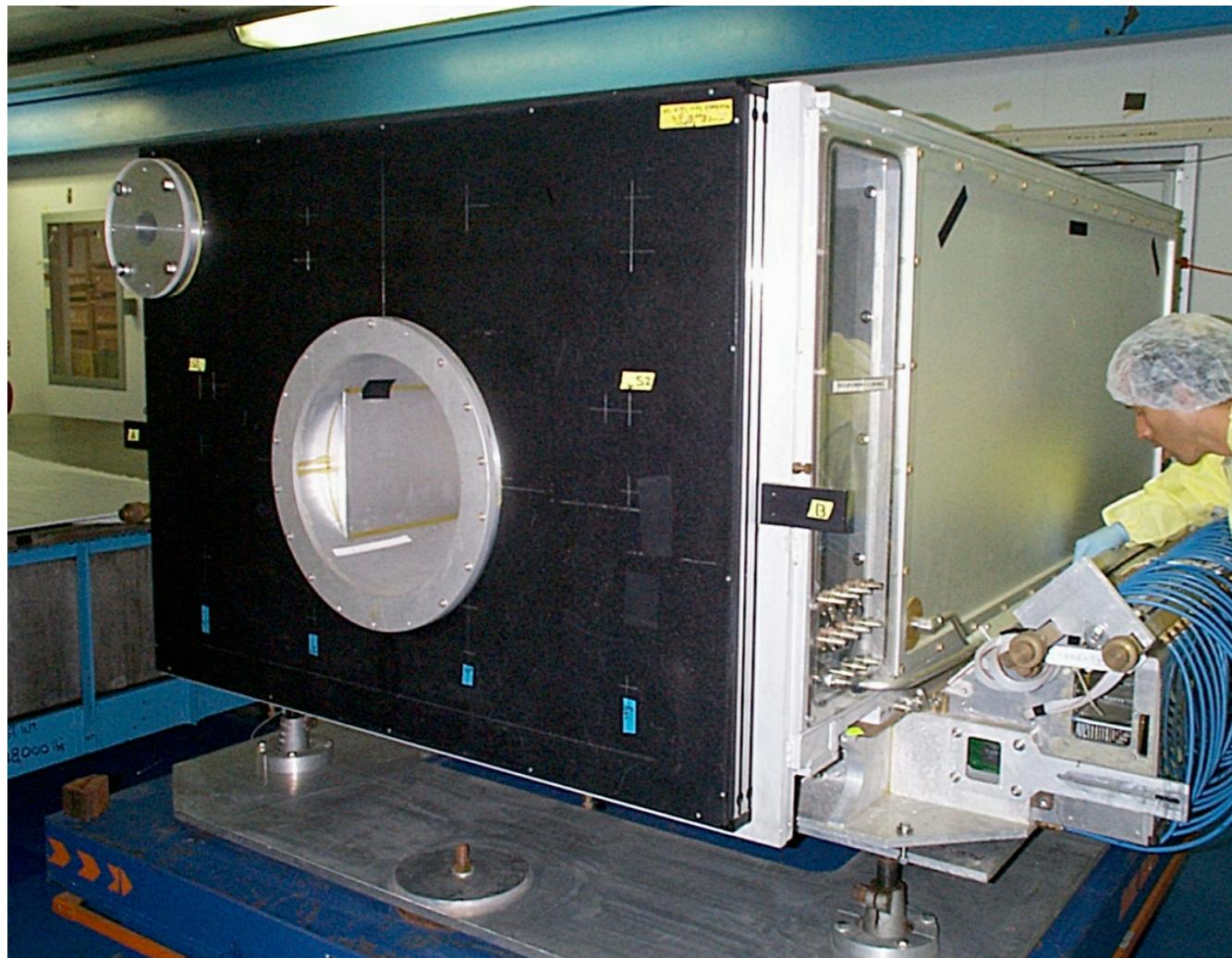
- Hadron production yield measurement for 120 GeV p + NuMI target.
- Hadron production yields/cross-sections for all thin targets using 120 GeV/c p's, 60 GeV  $\pi$ 's, K's and p's and 20 GeV  $\pi$ 's, K's and p's.
- $K^0$  production cross-section for all thin targets and beam momenta.
- Forward neutron production cross-section using the hadron and EM calorimeters.
- Exclusive cross-sections for p+p interactions at various momenta.

# Outline

## or, Where Are We on the MIPP Analyses?

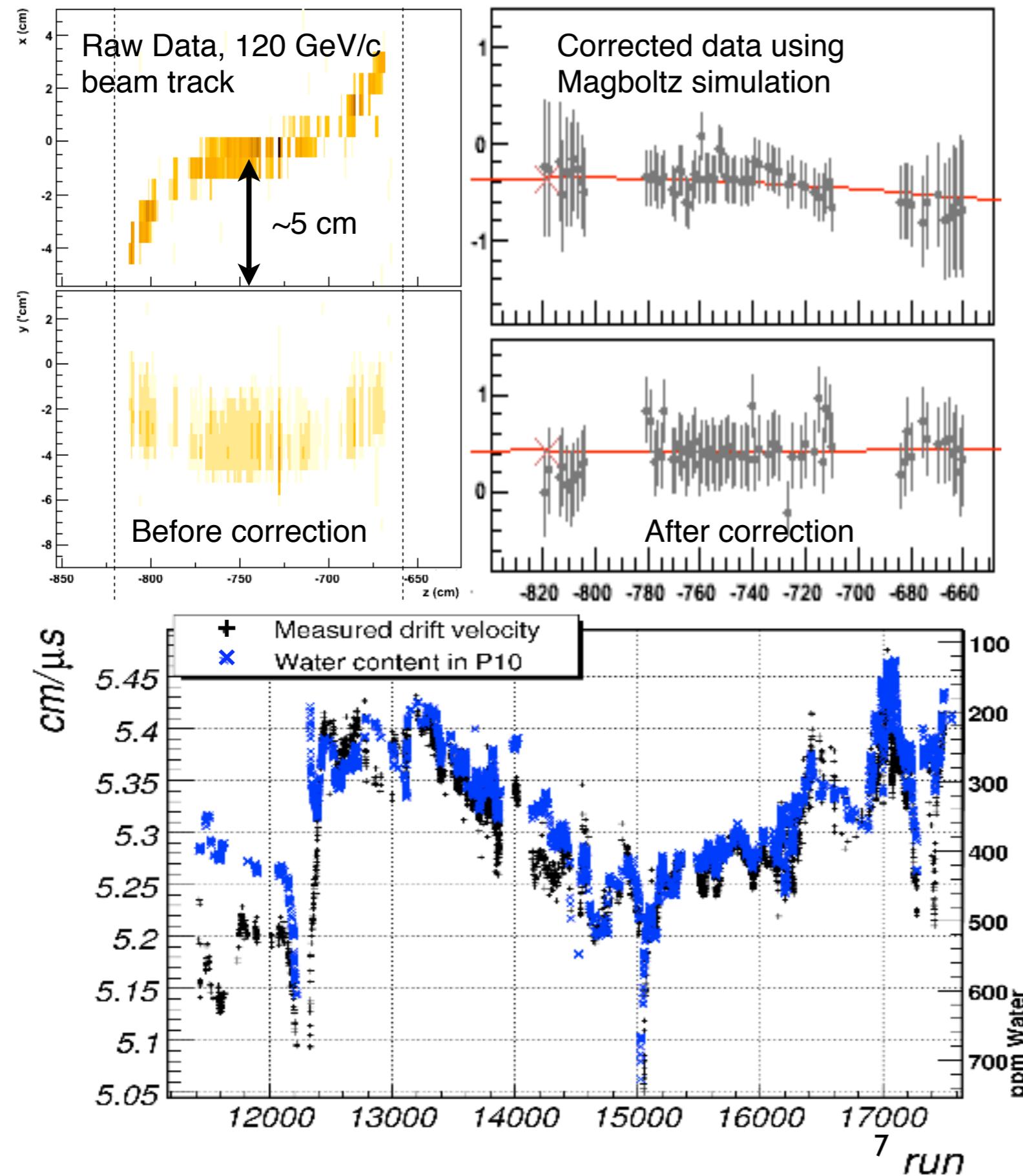
- Short answer: very close (months)
- Longer answer: we have faced a large number of challenges, but our event reconstruction, calibration and alignment are finalized as are the MC digitization.
- Production of final MC and real data sets are close to completion, which will allow collaborators to complete systematic studies needed for their analyses. PID algorithms are still being developed for most analyses.
- Today I will show:
  - details of the performances of our detector subsystems, as some of this is very relevant to the MIPP Upgrade.
  - status of the NuMI target and forward neutron production analyses, with time estimates for completion.

# Time Projection Chamber (TPC)



- Centerpiece of MIPP, originally built for the EOS experiment and used in several other prior experiments.
- Measures track trajectory in 3D: (x,z) position → pad locations, y position → drift time.
- Active volume of ~1 m<sup>3</sup> and a resolution of ~0.5 cm<sup>3</sup>.
- PID via  $\langle dE/dx \rangle$  below ~1 GeV/c.

# TPC Calibrations



- Inhomogeneous magnetic field causes drift electrons to deviate from straight-line path to pad plane on bottom on TPC. Deviations of up to ~5 cm are observed!
- Using a map of the magnetic field and the Magboltz simulation, we correct these ExB drift effects to the level of ~90% (~2 mm worst case).
- Electron drift velocity is found to be run/time dependent: sensitive to the water contamination in the P10 gas!
- Run-by-run corrections to the drift velocity are made and  $\delta v_D / v_D \sim 1\%$ .

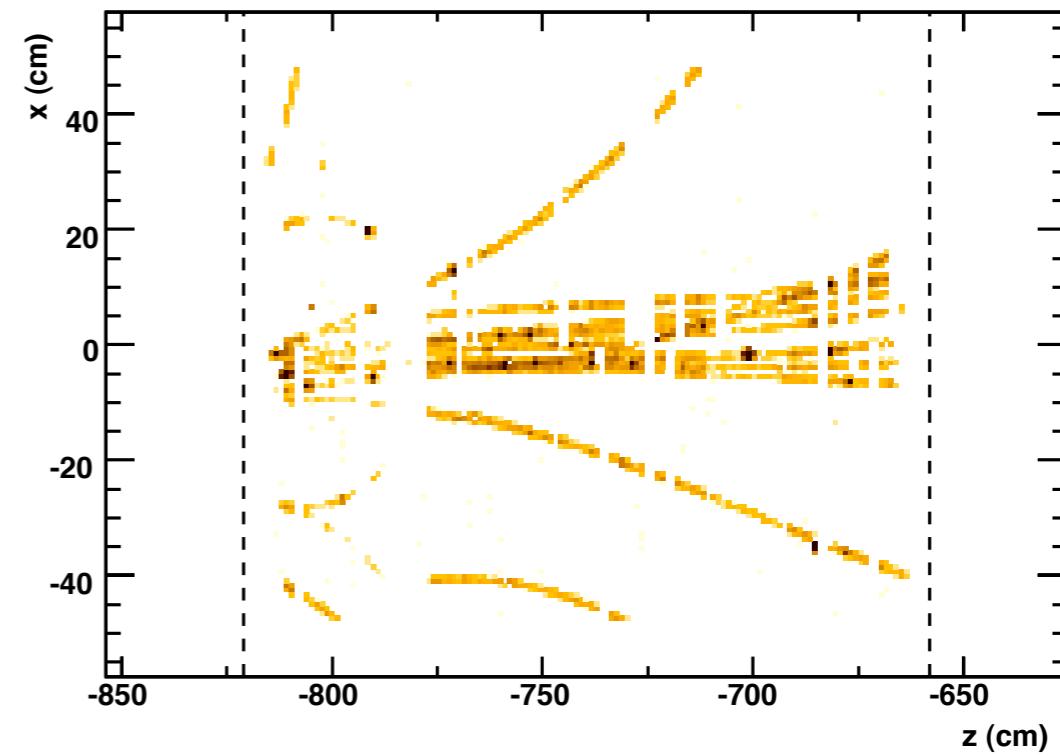
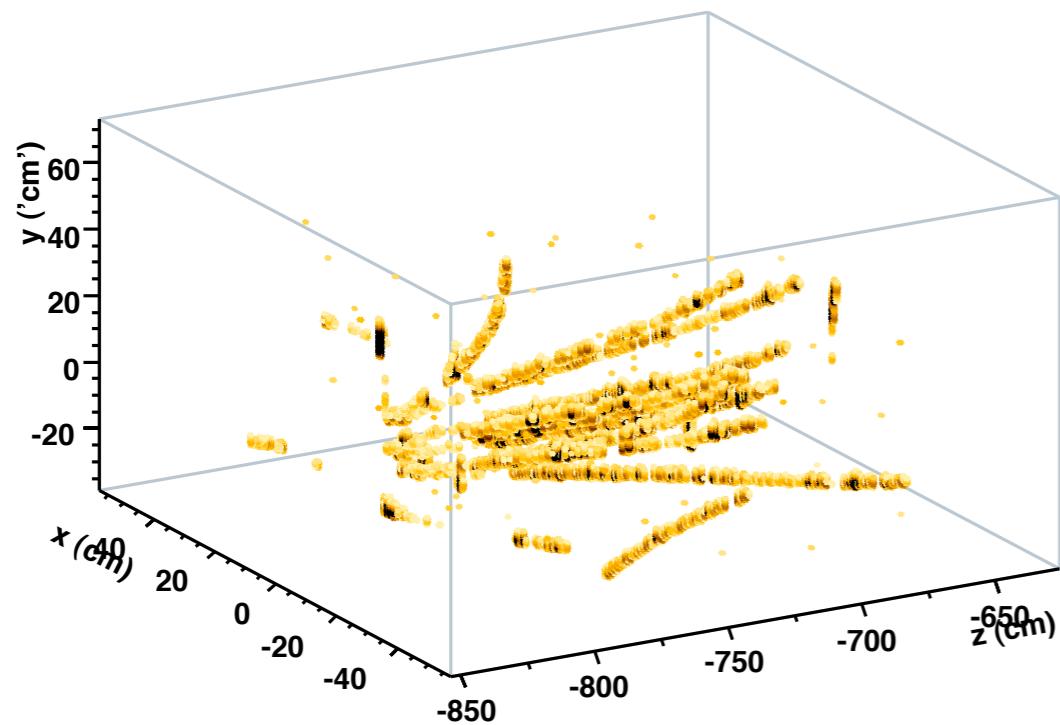
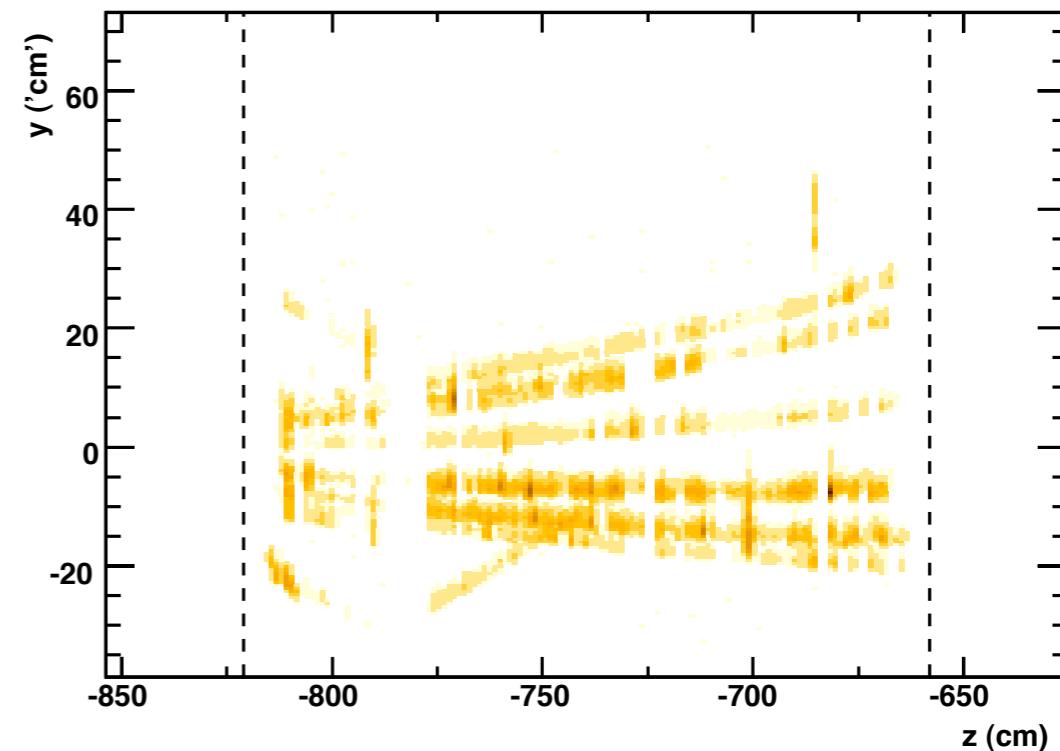
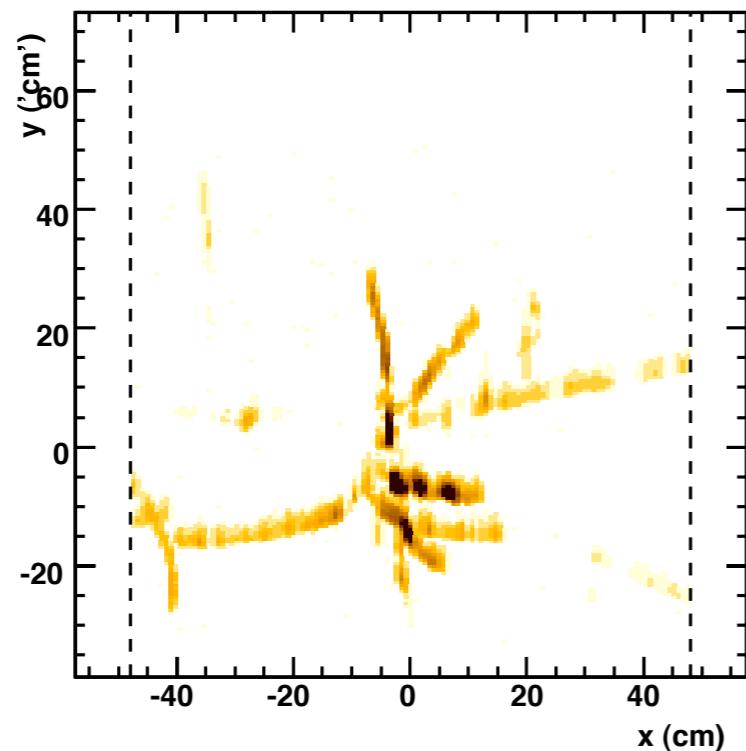
# TPC Reconstruction

MIPP (FNAL E907)

Mom.: 120 GeV/c  
Target: NuMI  
Run: 15118  
SubRun: 0  
Event: 33

Sun Jul 24 2005  
13:10:30.411046

\*\*\* Trigger \*\*\*  
Beam  
Word: 0080  
Bits: 80D7



Start with raw TPC data...

# TPC Reconstruction

MIPP (FNAL E907)

Mom.: 120 GeV/c

Target: NuMI

Run: 15118

SubRun: 0

Event: 33

Sun Jul 24 2005

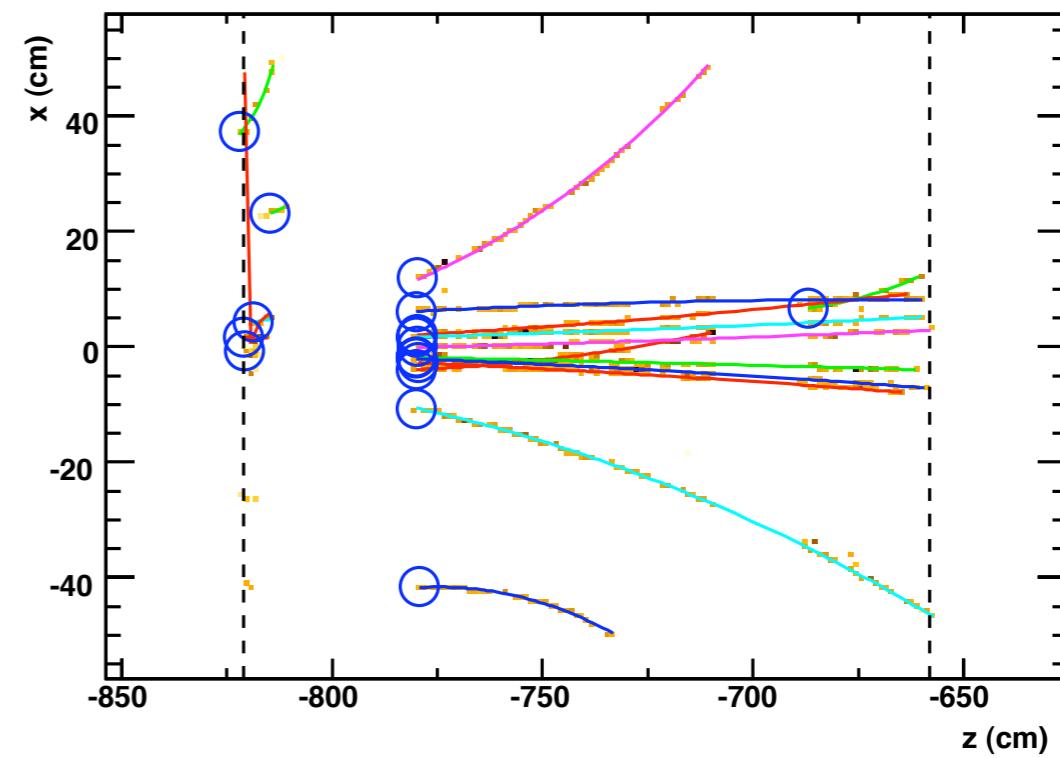
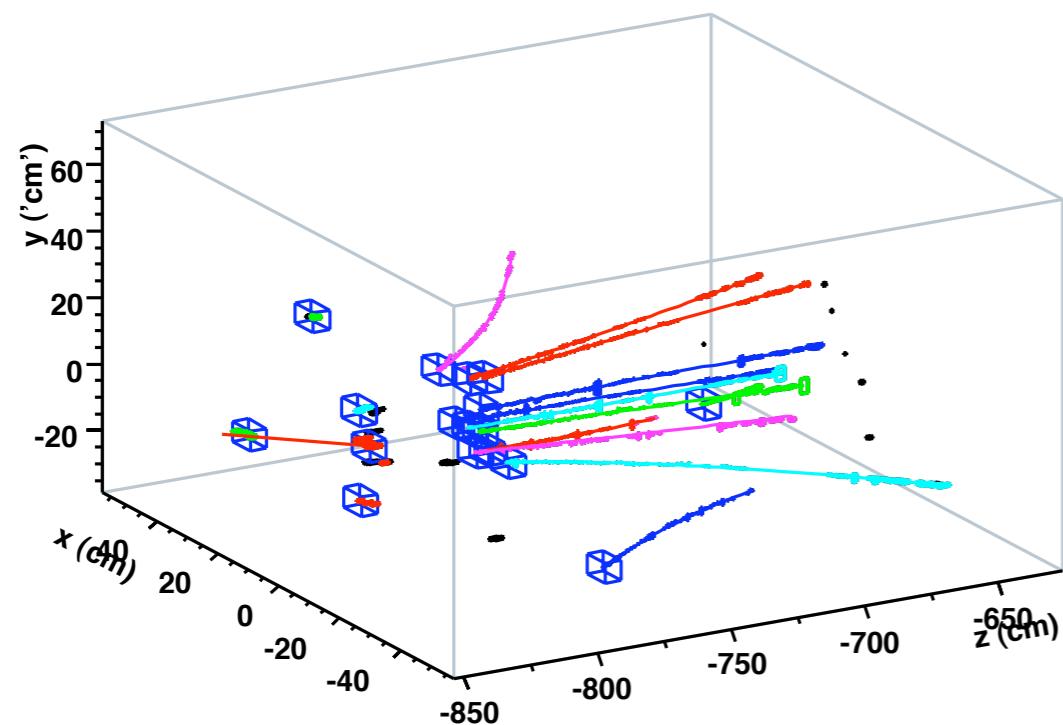
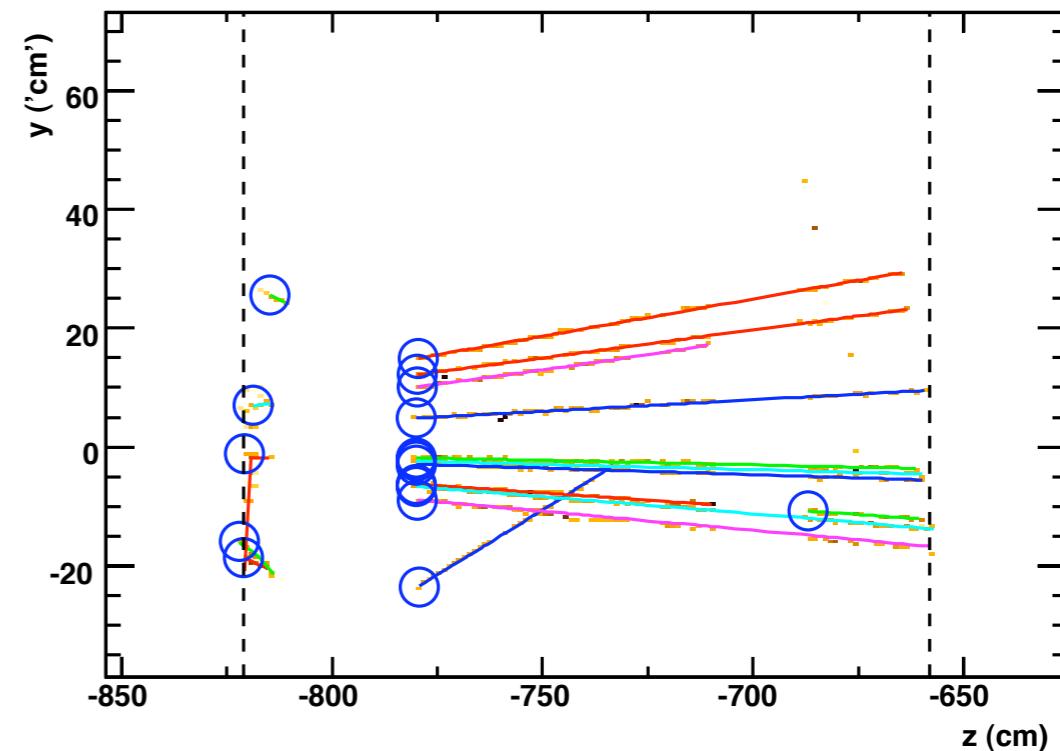
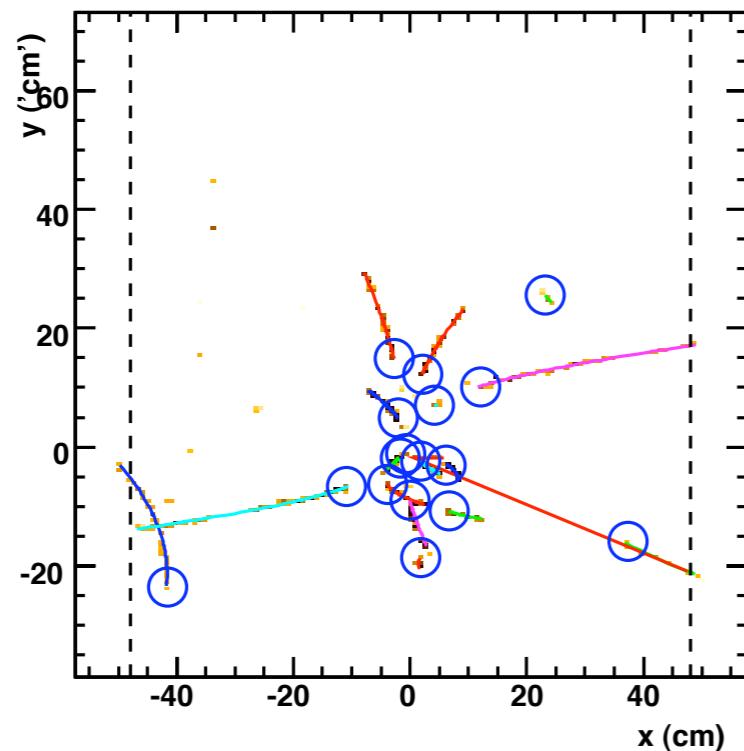
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\*\*\* Trigger \*\*\*

Beam

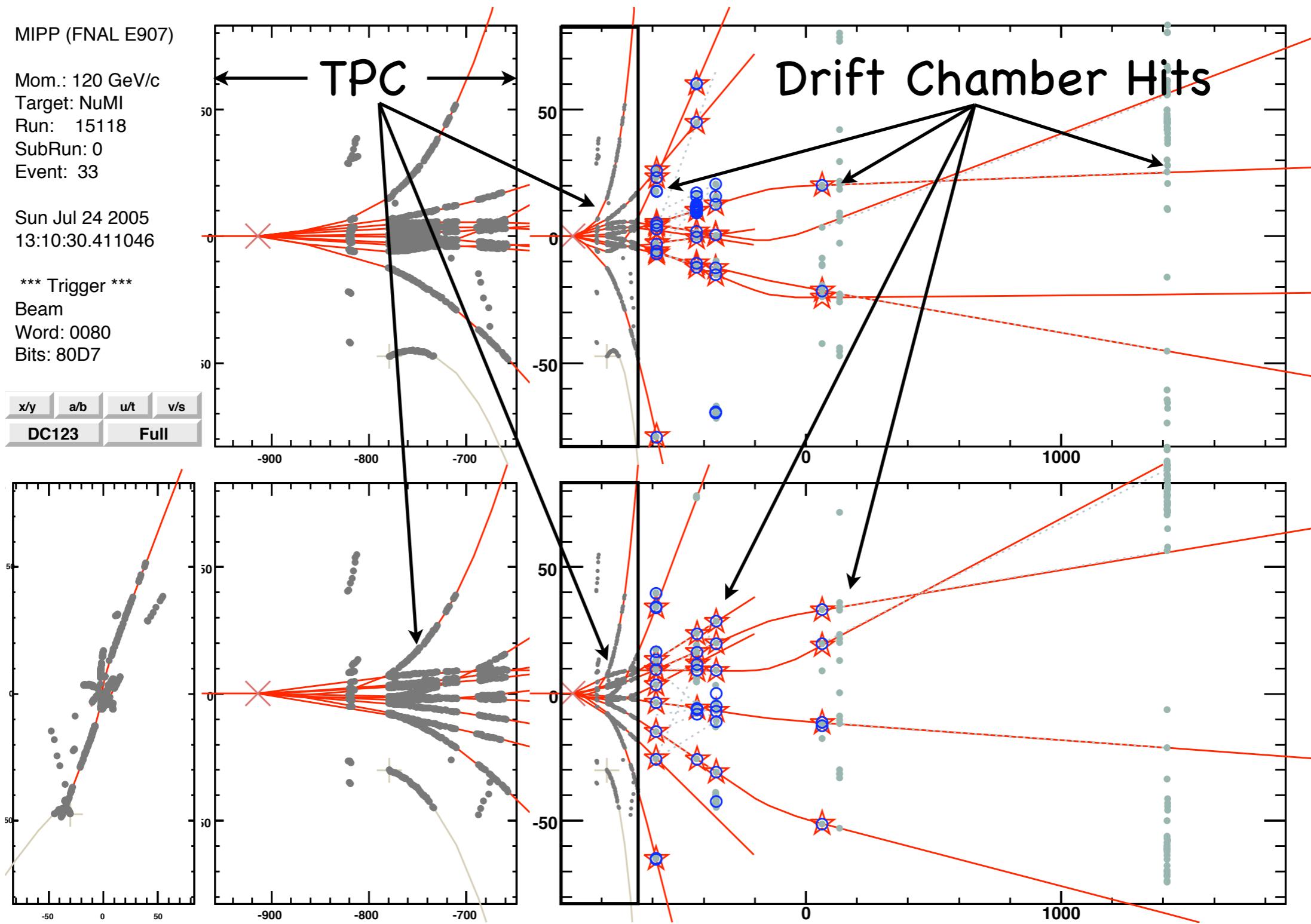
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Bits: 80D7



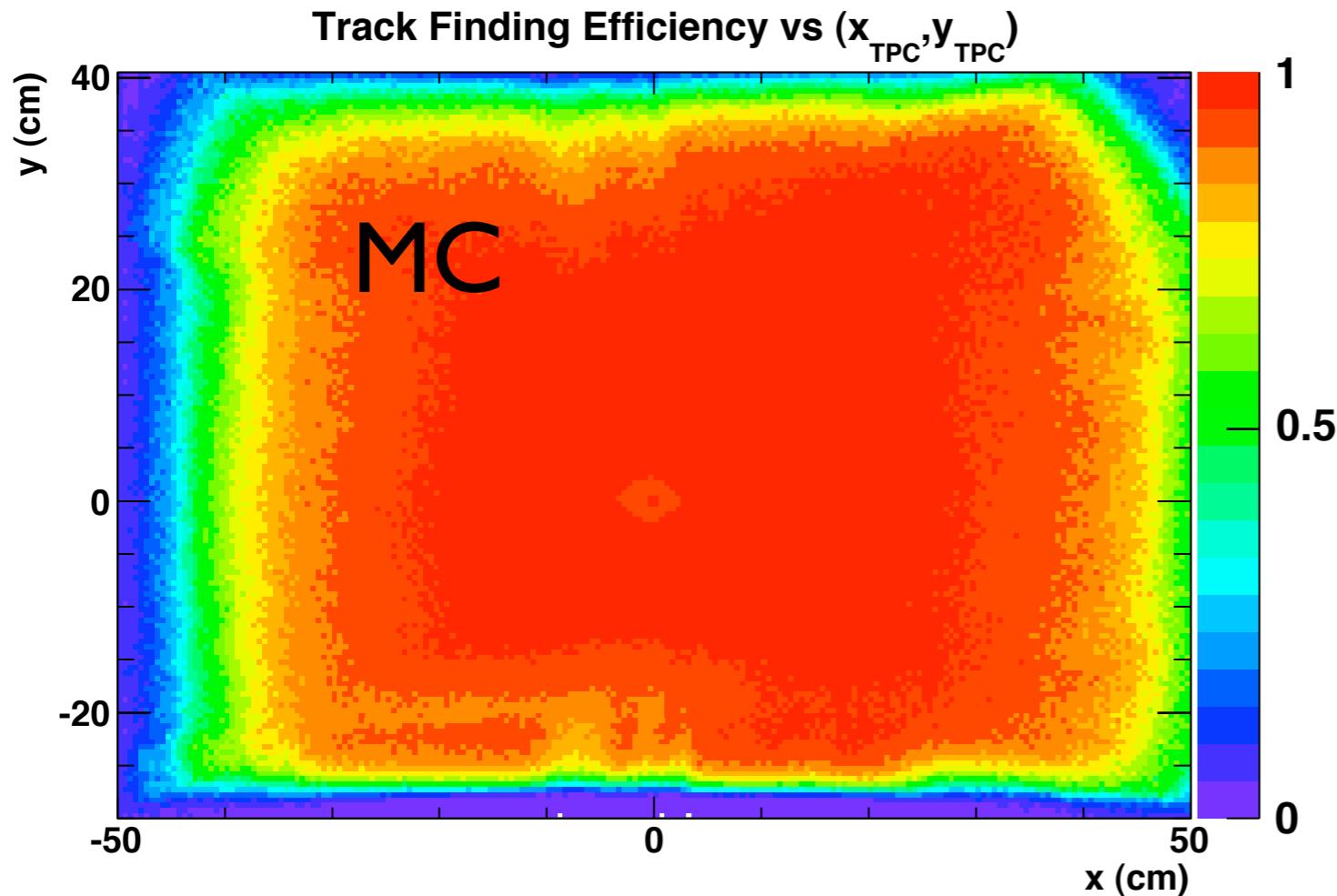
Form track segments from hits...

# Global Track Reconstruction



TPC track segments are matched to downstream drift chamber hits, momentum is determined from bend in both magnets.

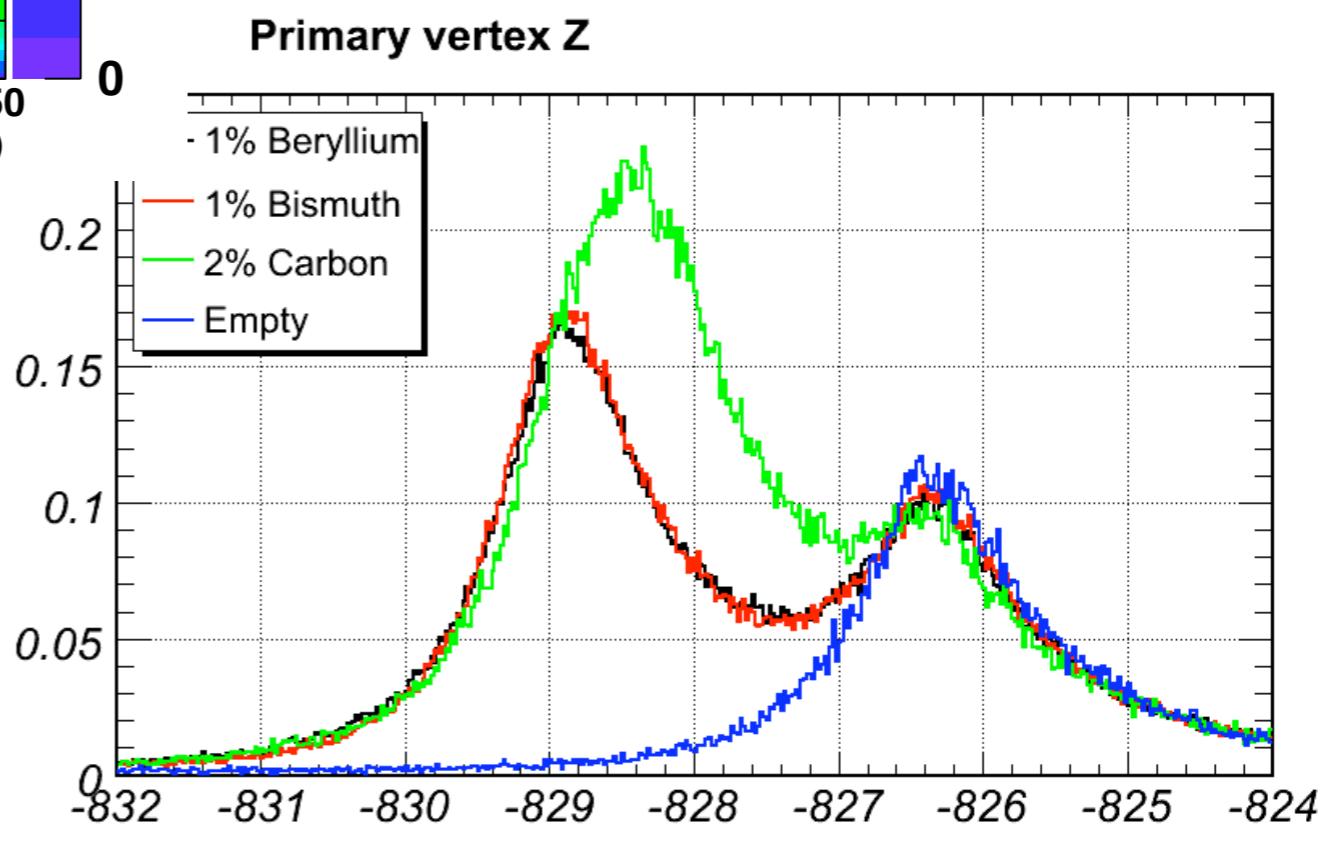
# Track Finding and Vertexing



Vertex-constrained fit resolution improves momentum resolution by  $\sim 30\%$ . Beam-transverse vertex position resolution is  $\sim 2$  mm, longitudinal position resolution is  $\sim 8$  mm.

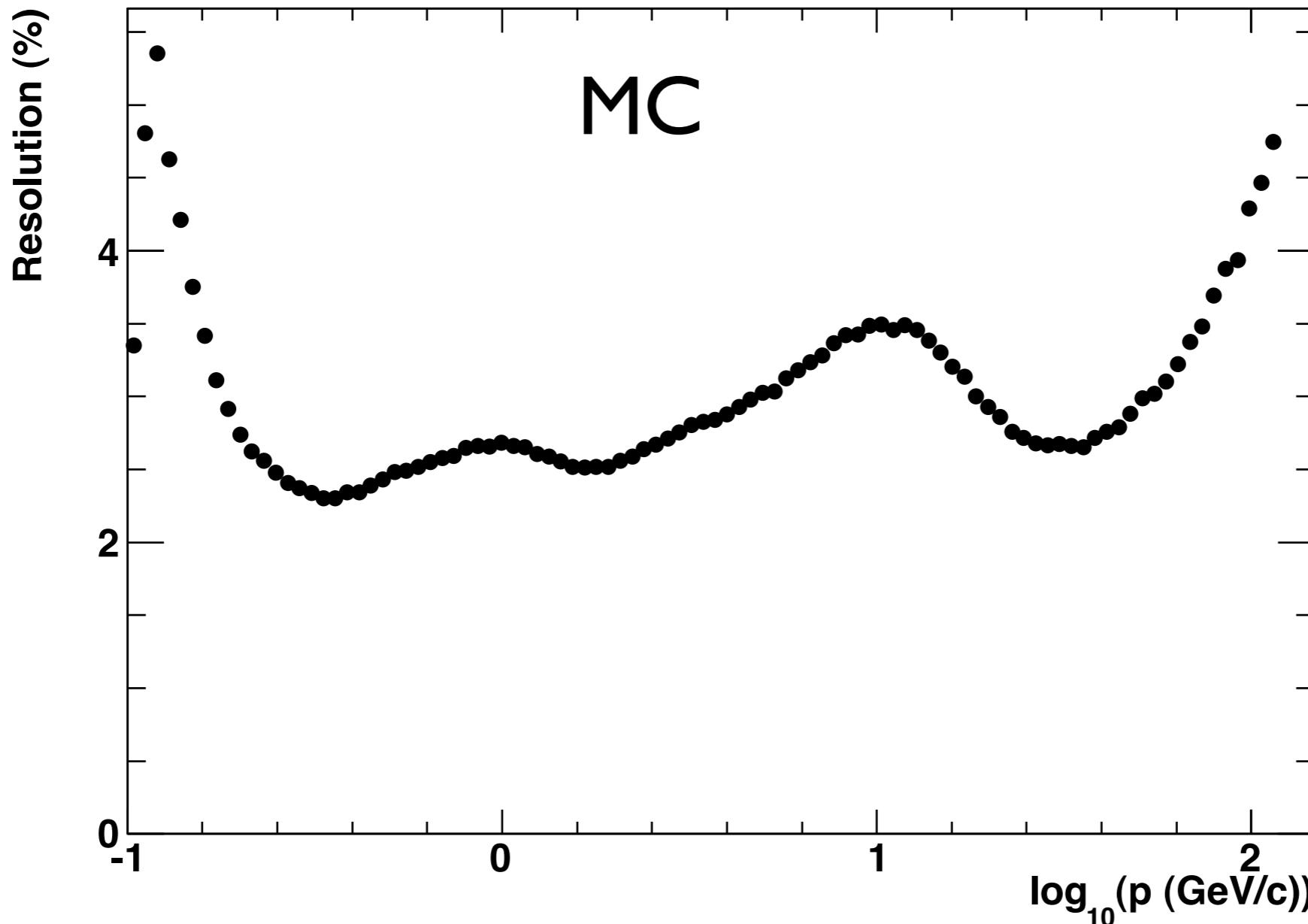
Very high track-finding efficiency.

Also very well modeled, MC takes into account time-dependent hot/dead channel maps.



# Momentum Resolution

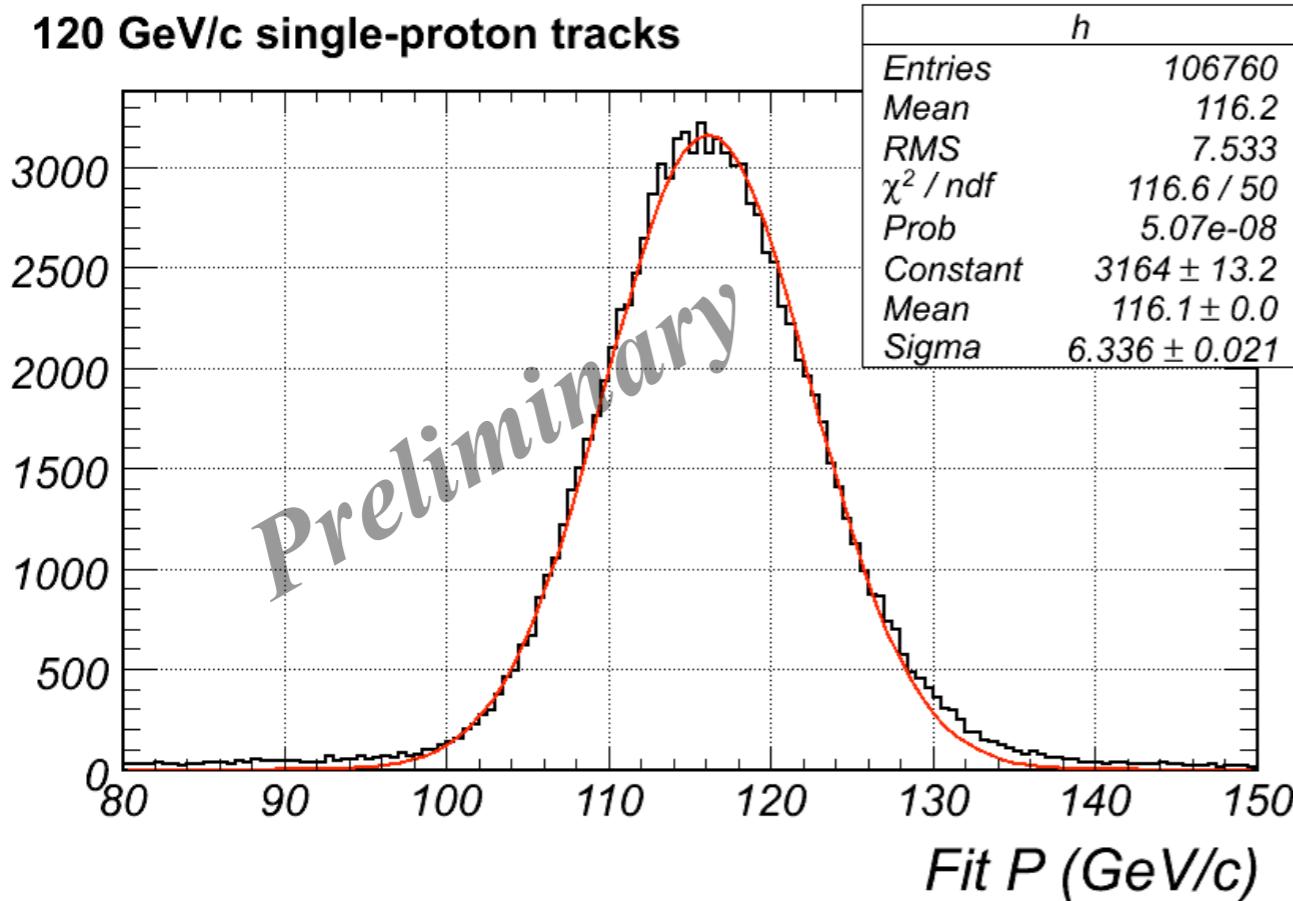
Resolution vs.  $\log_{10}(p)$



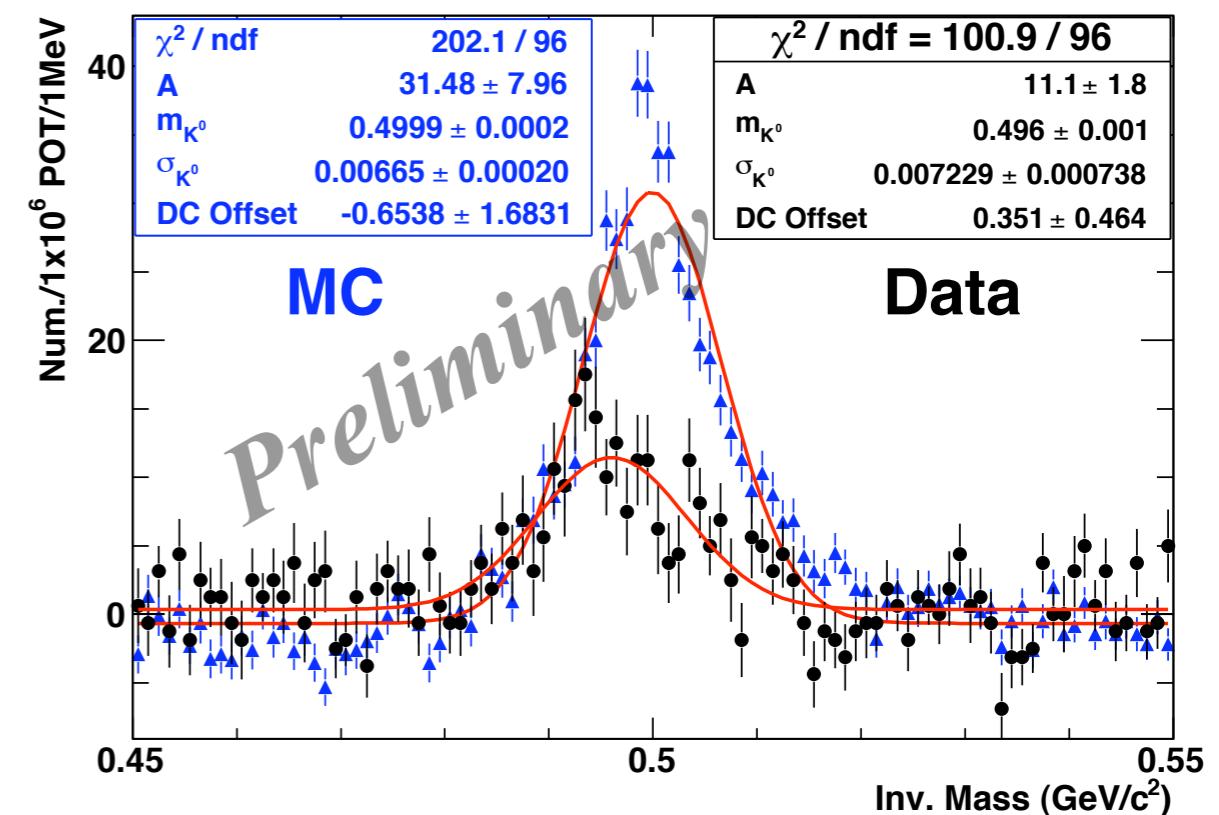
- Resolution determined by fitting central peaks of slices of  $d\mu/\mu$  to Gaussian.
- Momentum resolution is  $< \sim 5\%$
- Transverse momentum resolution is  $< 0.02 \text{ GeV}$

# Absolute Energy Scale

120 GeV/c single-proton tracks



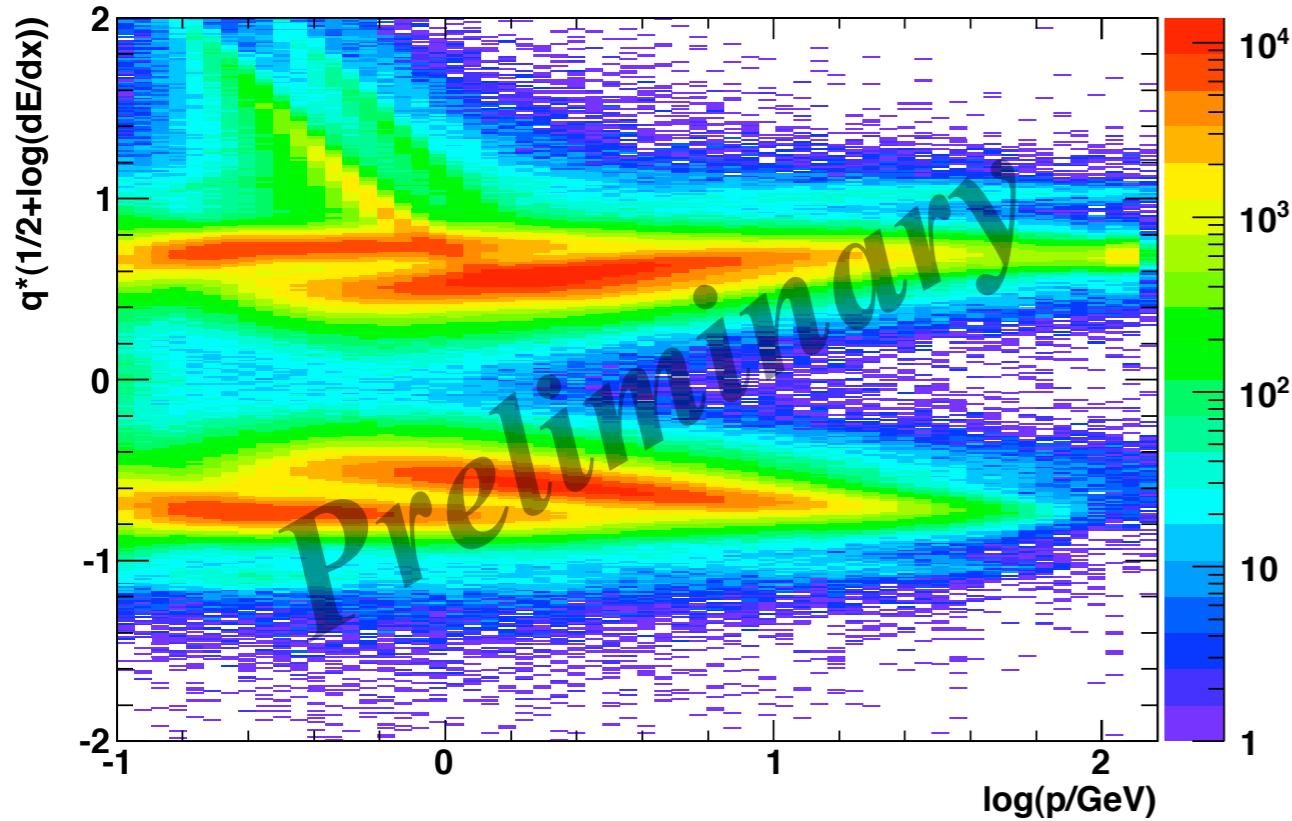
Bkg-Subtracted Inv. Mass Distribution, NuMI MC, dz Cut



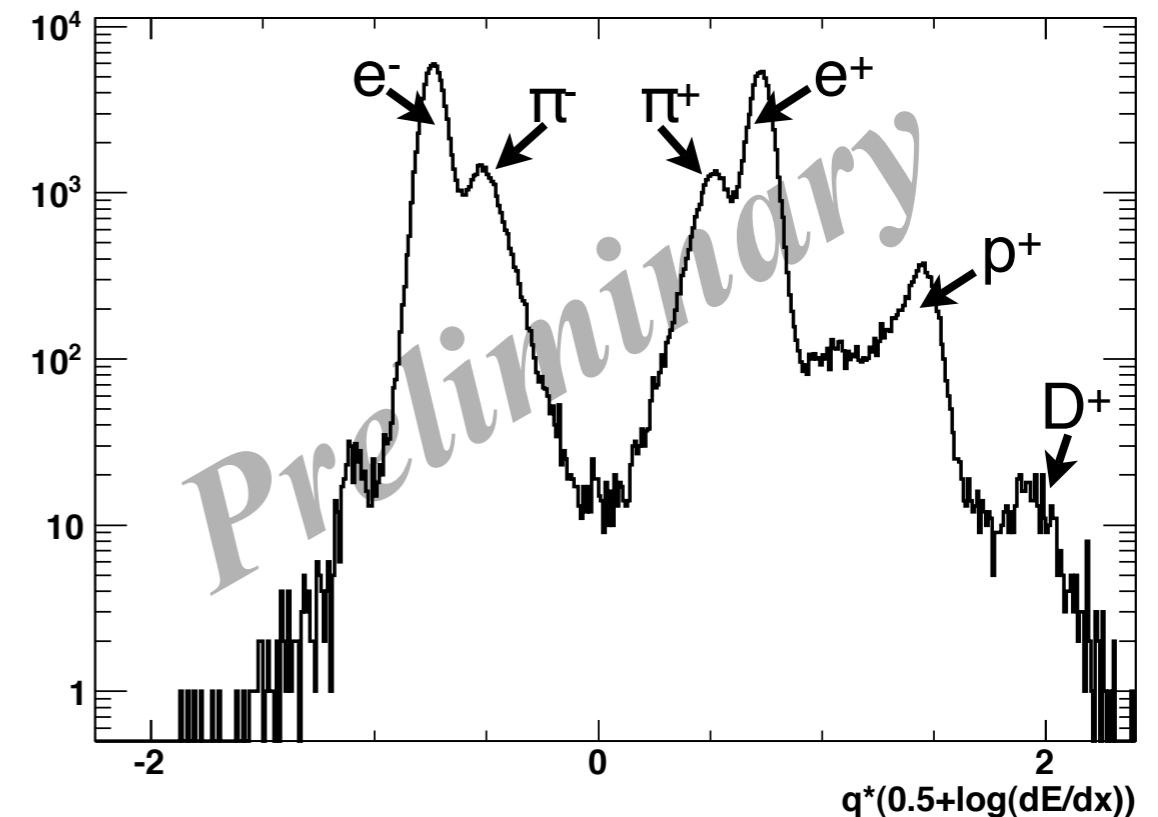
- Comparison of reconstructed MI proton momenta to expected value of 119.6 GeV/c indicates we are low by 3%.
- Reconstructed  $K^0$  invariant mass using tracks with  $p < 2$  GeV/c indicates we are low by ~1%.
- Side note: Preliminary  $K^0$  study indicates that Fluka prediction of  $K^0$  production in NuMI target is too high by a factor of ~2.6!

# TPC PID Performance

TPC  $\langle dE/dx \rangle$  vs. P, Full NuMI Data Set

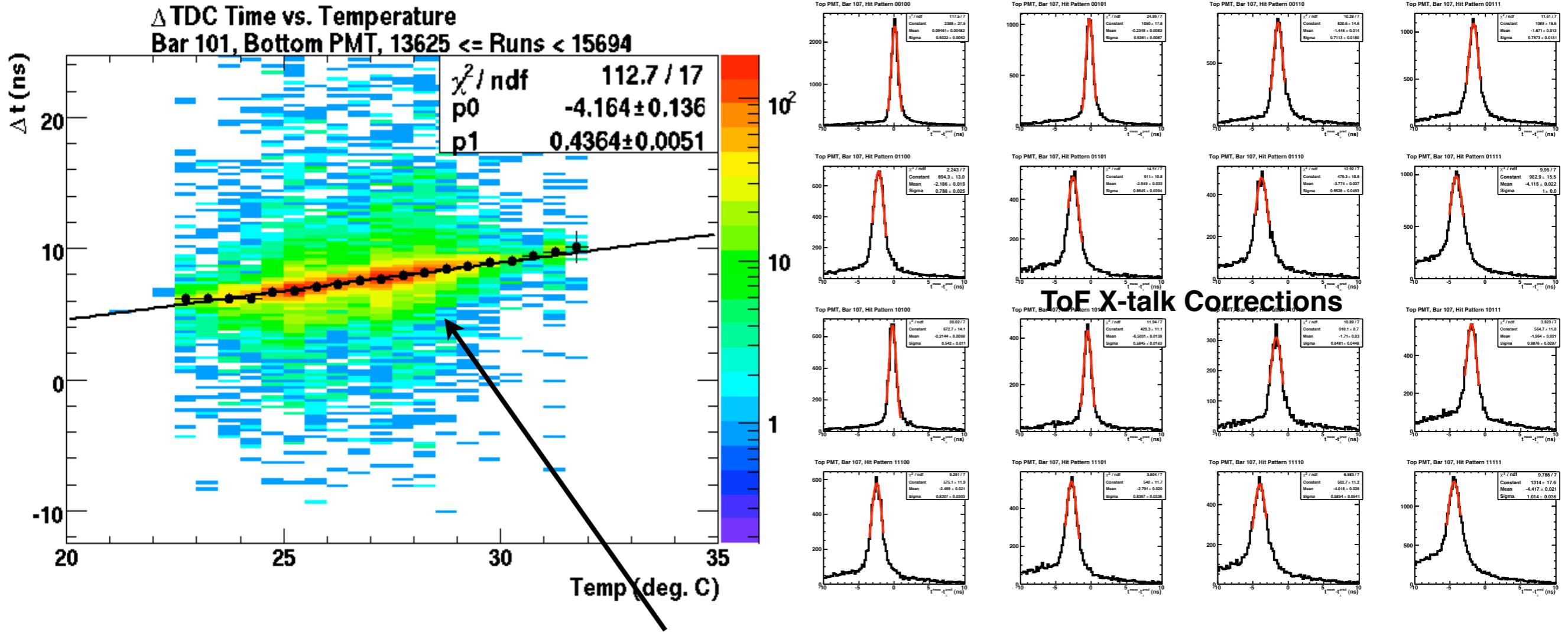


TPC  $\langle dE/dx \rangle$  for  $0.30 < P < 0.33 \text{ GeV}/c$



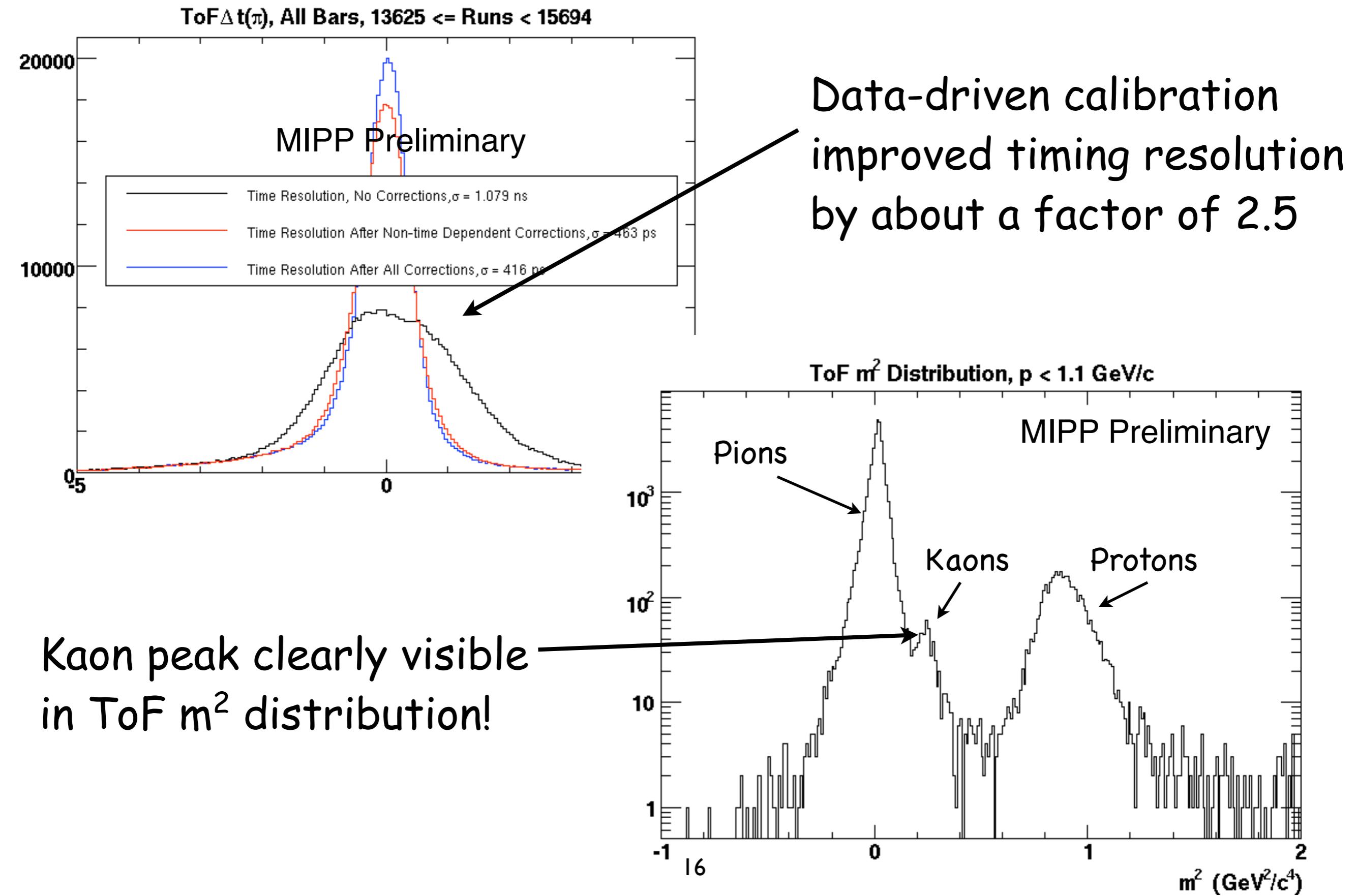
- TPC data are calibrated such that  $\langle dE/dx \rangle(\pi)$  is 1 for  $p = 0.4 \text{ GeV}/c$  and give expected Bethe-Bloch functional form.
- $\langle dE/dx \rangle$  resolution  $\sim 10\%$ .
- Clean  $\pi$ ,  $p$  separation between 0.2 and 1.2  $\text{GeV}/c$ .

# ToF PID Performance

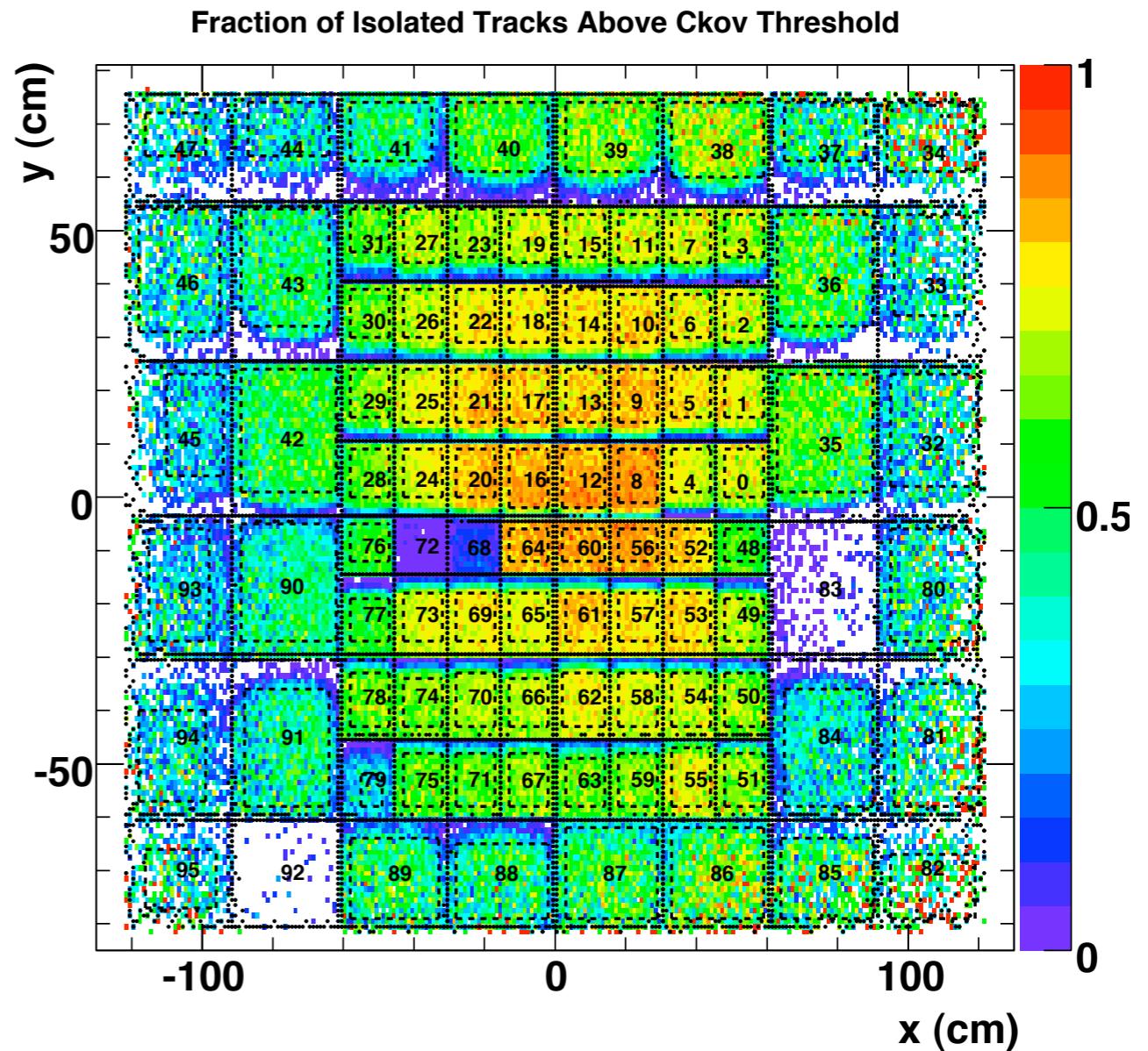
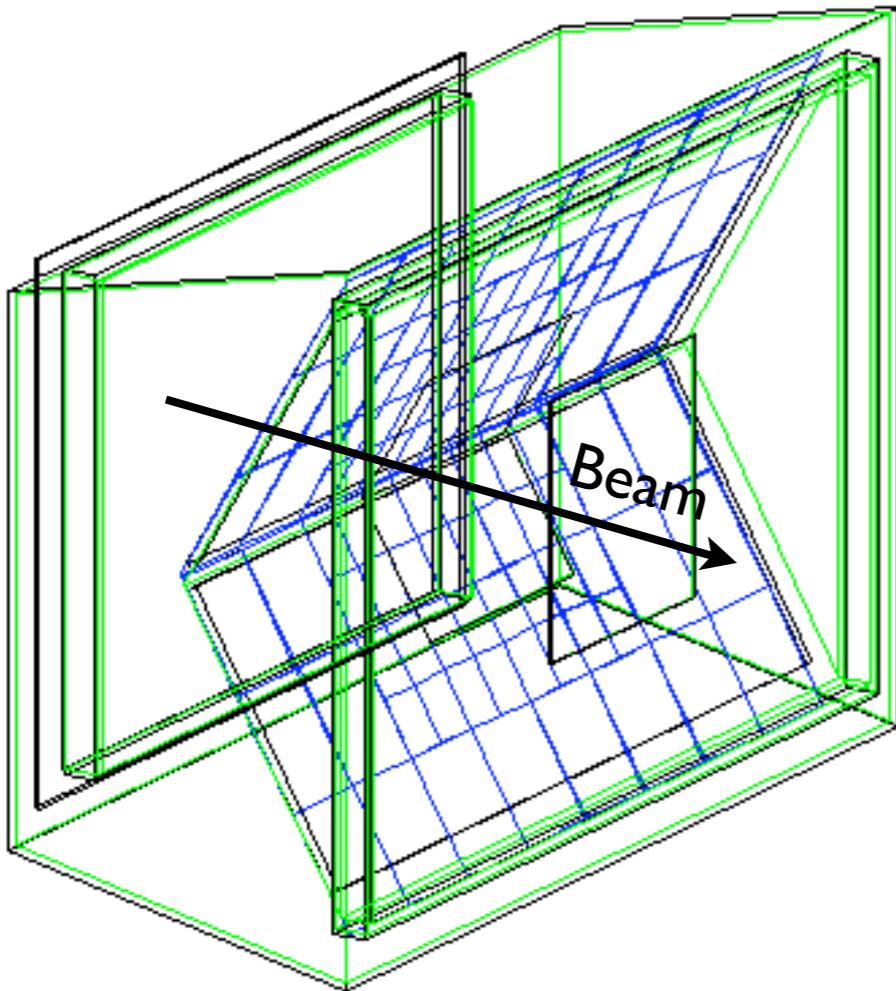


- Measured time affected by temperature fluctuations ( $\Delta t \sim 500 \text{ ps}/^\circ\text{C}$ ) and amplitude of the signal ( $\Delta t \sim 10 \text{ ps}/\text{ADC}$ ).
- Capacitive cross-talk in all channels shifts measured time
  - requiring no hits in adjacent channels rejects ~90% of ToF data
- all ~1000 combinations of 5-hit bars calibrated separately. We have recovered all ToF data.

# ToF PID Performance



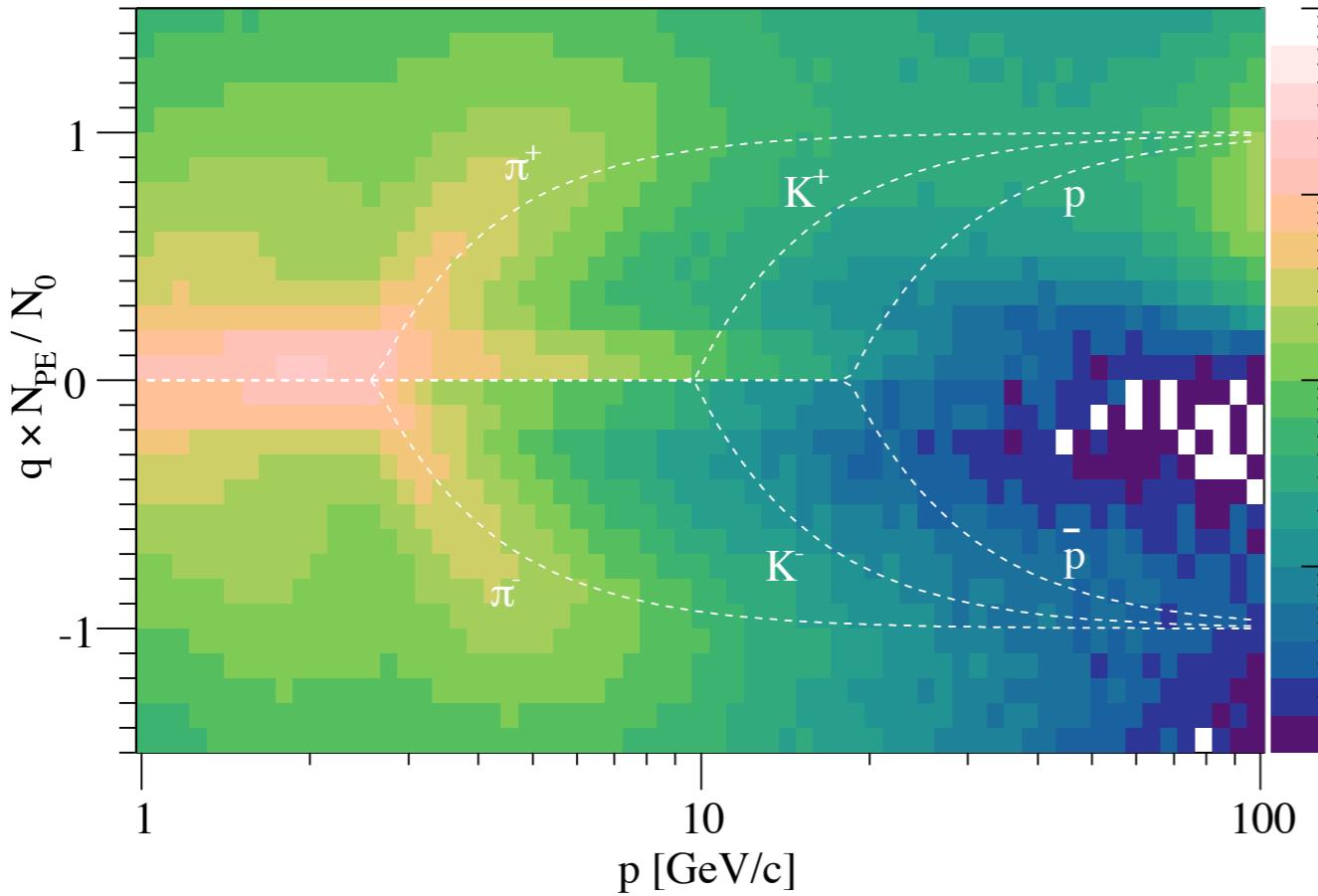
# Ckov Performance



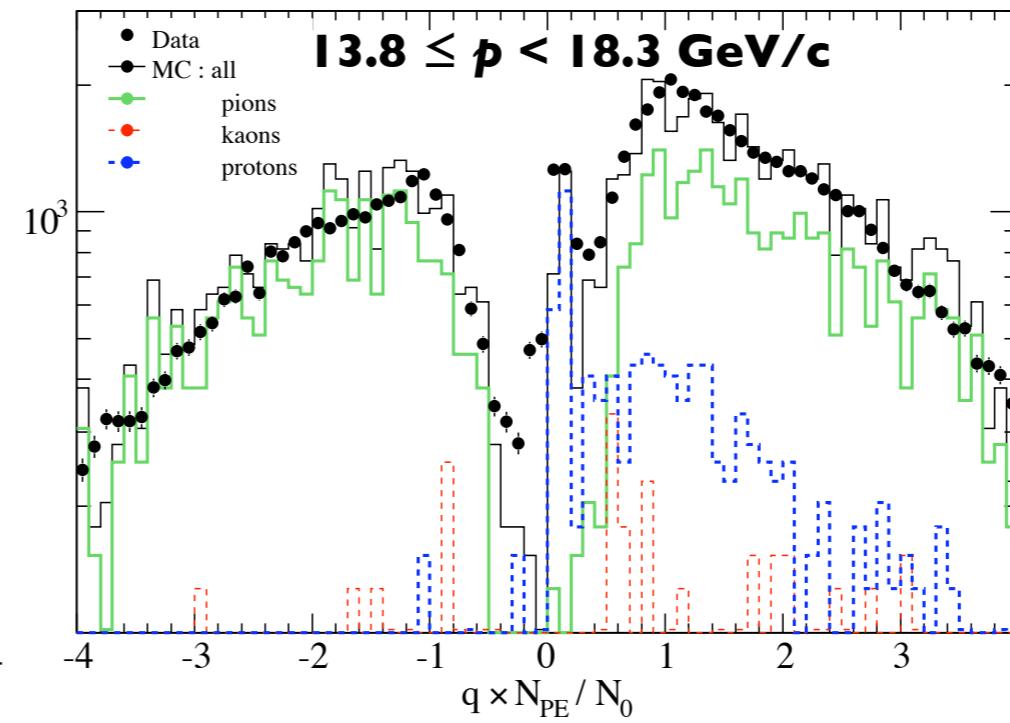
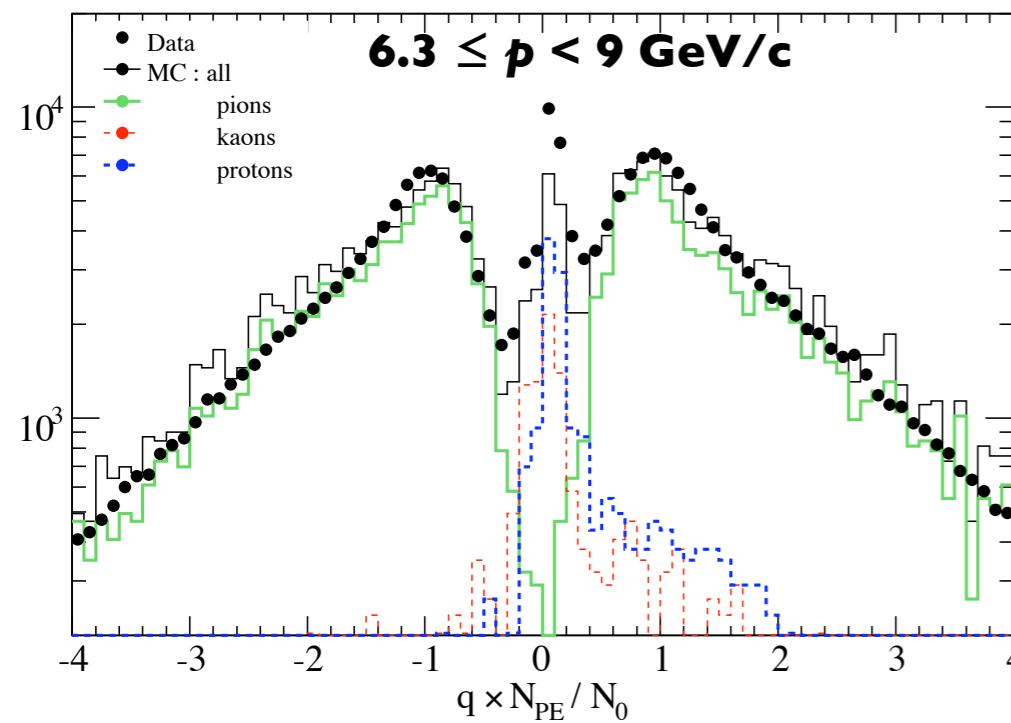
- Data-driven calibration of 96 mirrors found detector response  $\sim 2x$  weaker than anticipated ( $< 10 \text{ pe}/\beta=1 \text{ track}$ ).
- Will need to take into account 4 dead (out of 96) PMT channels.
- Must only consider “isolated” tracks passing through mirrors; reject  $\sim 50\%$  of Ckov data.

# Ckov PID Performance

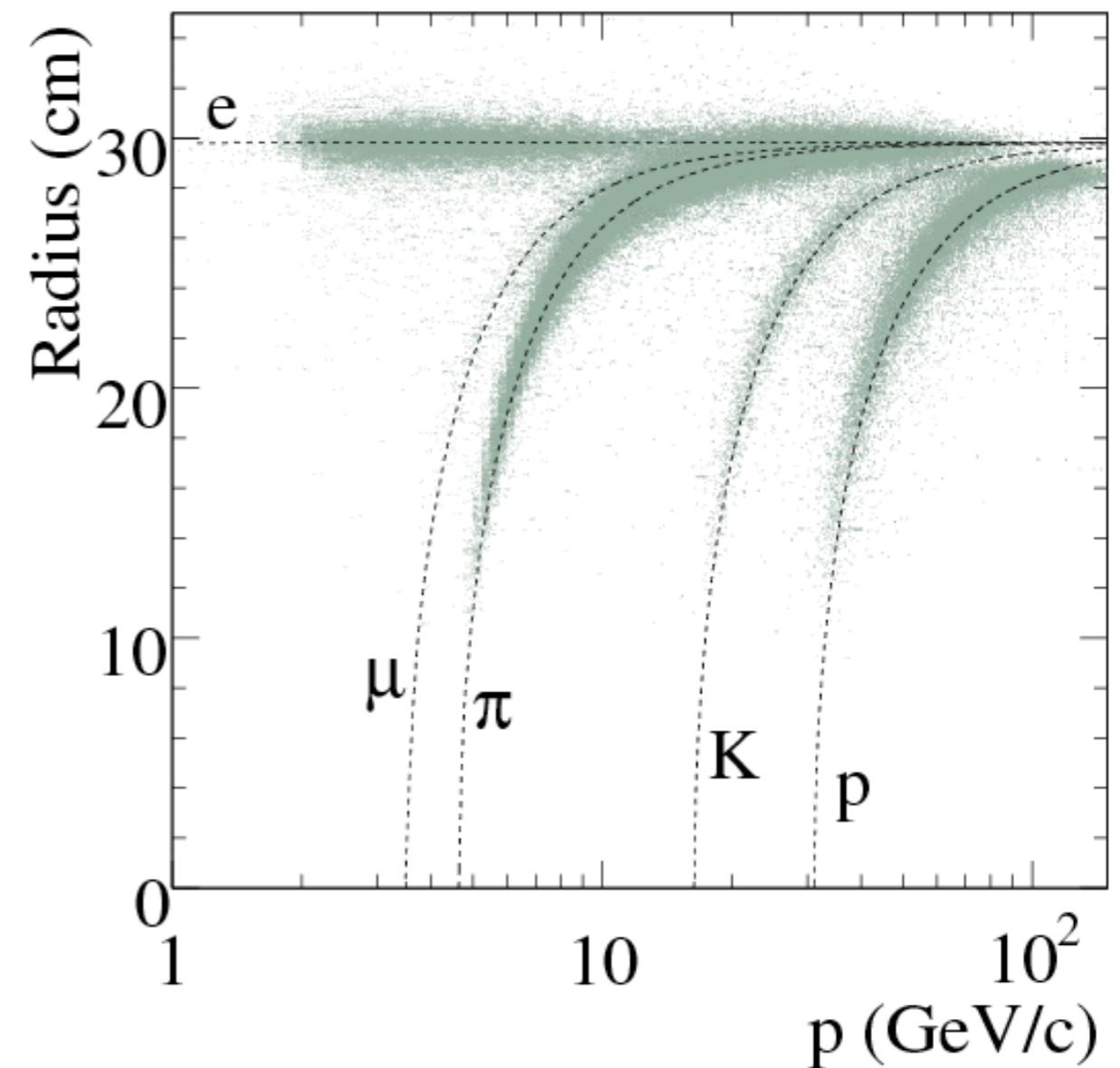
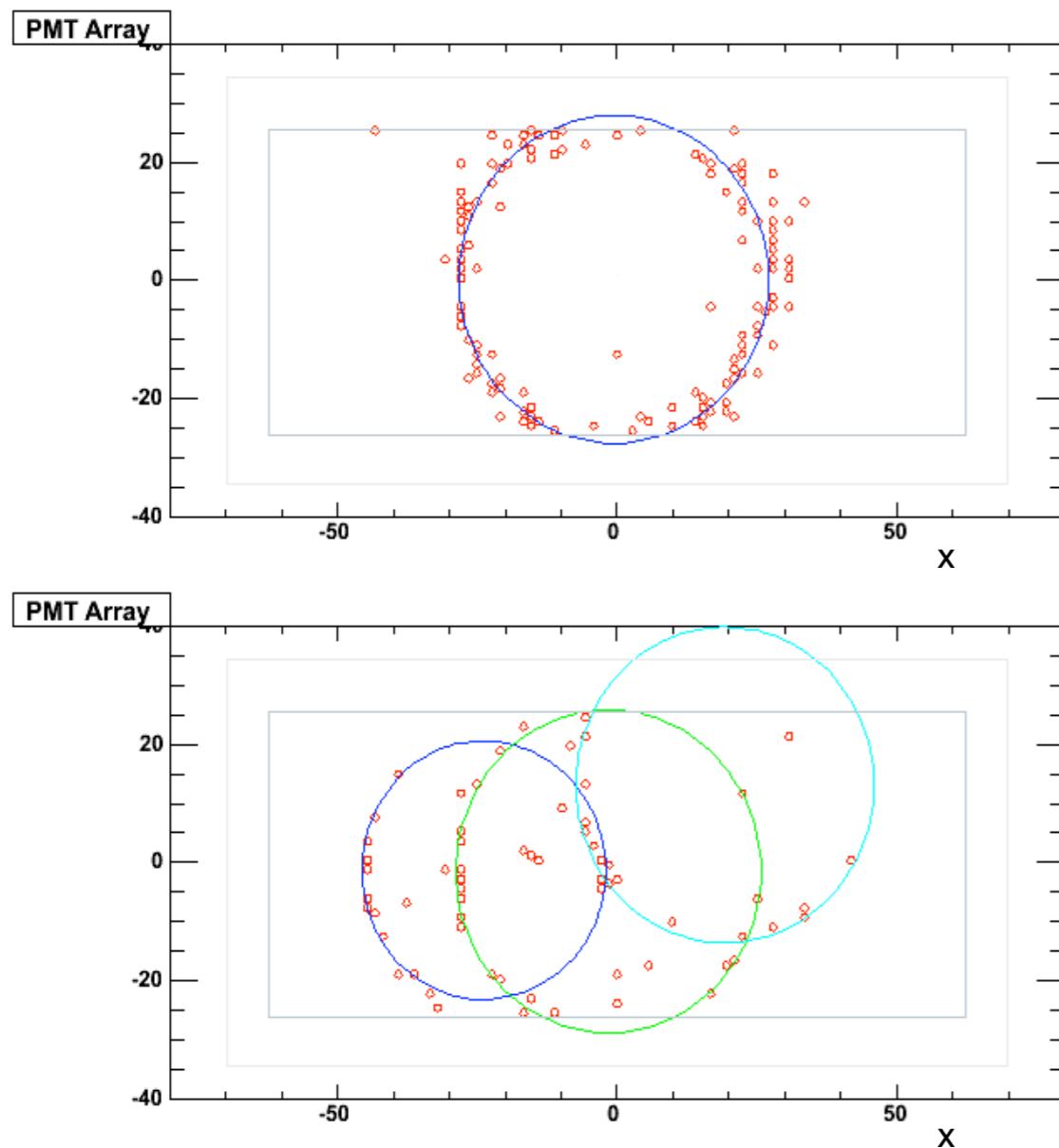
Ckov Detector Response



- Since all mirrors have a different response, each measurement of  $N_{PE}$  is normalized to that of a  $\beta=1$  particle.
- Pion “turn-on” clearly visible; proton “turn-on” also visible in slices of momentum.
- Shape of normalized response distribution in MC agrees very well with data.

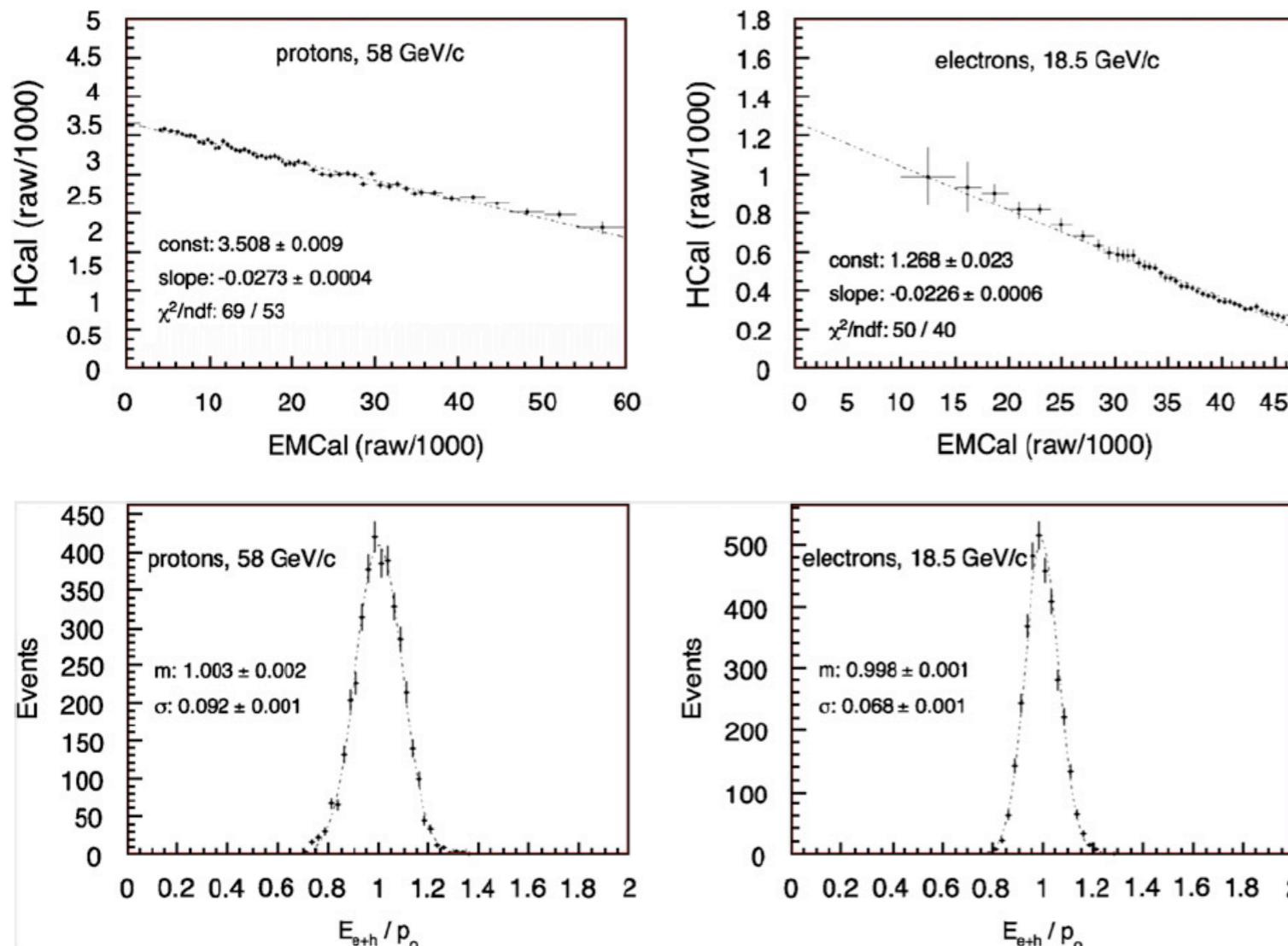


# RICH PID Performance

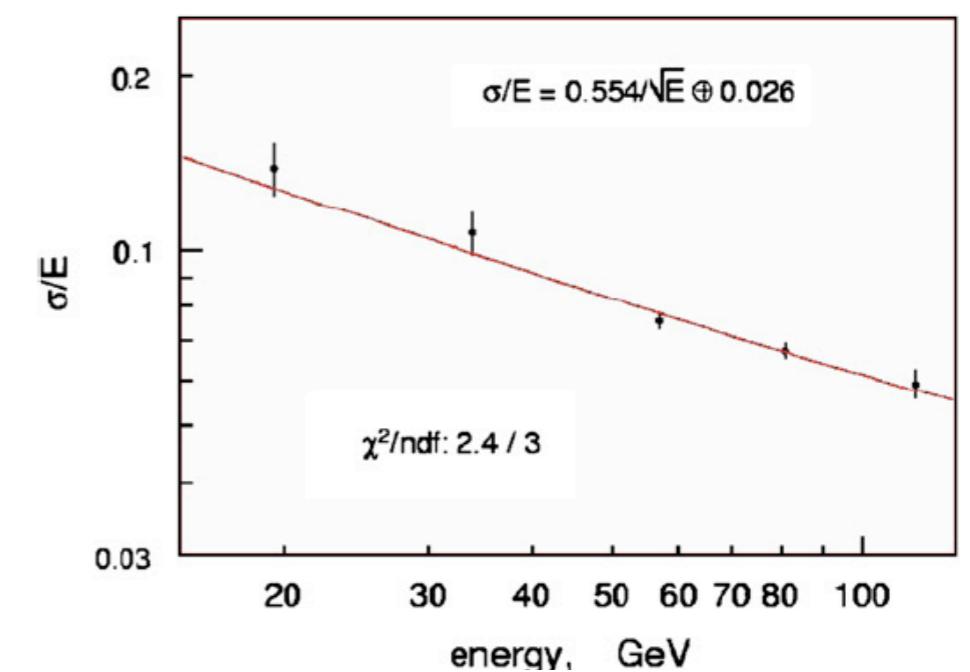


- Ckov light ring formed on array of ~2300 1/2" PMTs.
- Ring radius  $\sim$  Ckov angle  $\sim$  velocity.
- $3\sigma$   $\pi/K$  separation up to 80 GeV/c,  $3\sigma$   $p/K$  separation up to 120 GeV/c

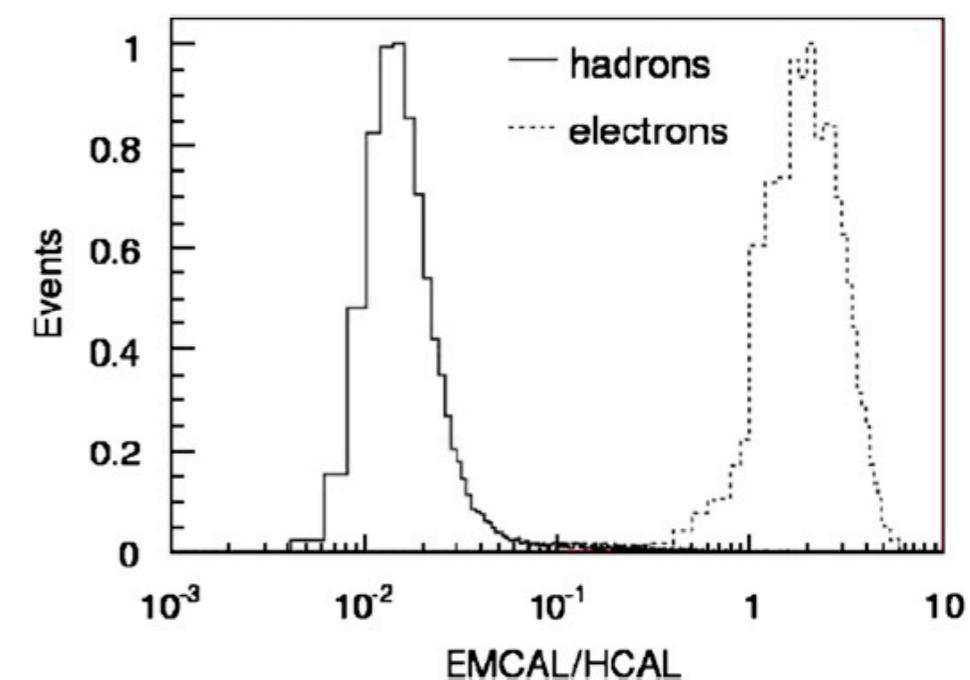
# Calorimeter Performance



- Detectors were calibrated using proton and electron beams.



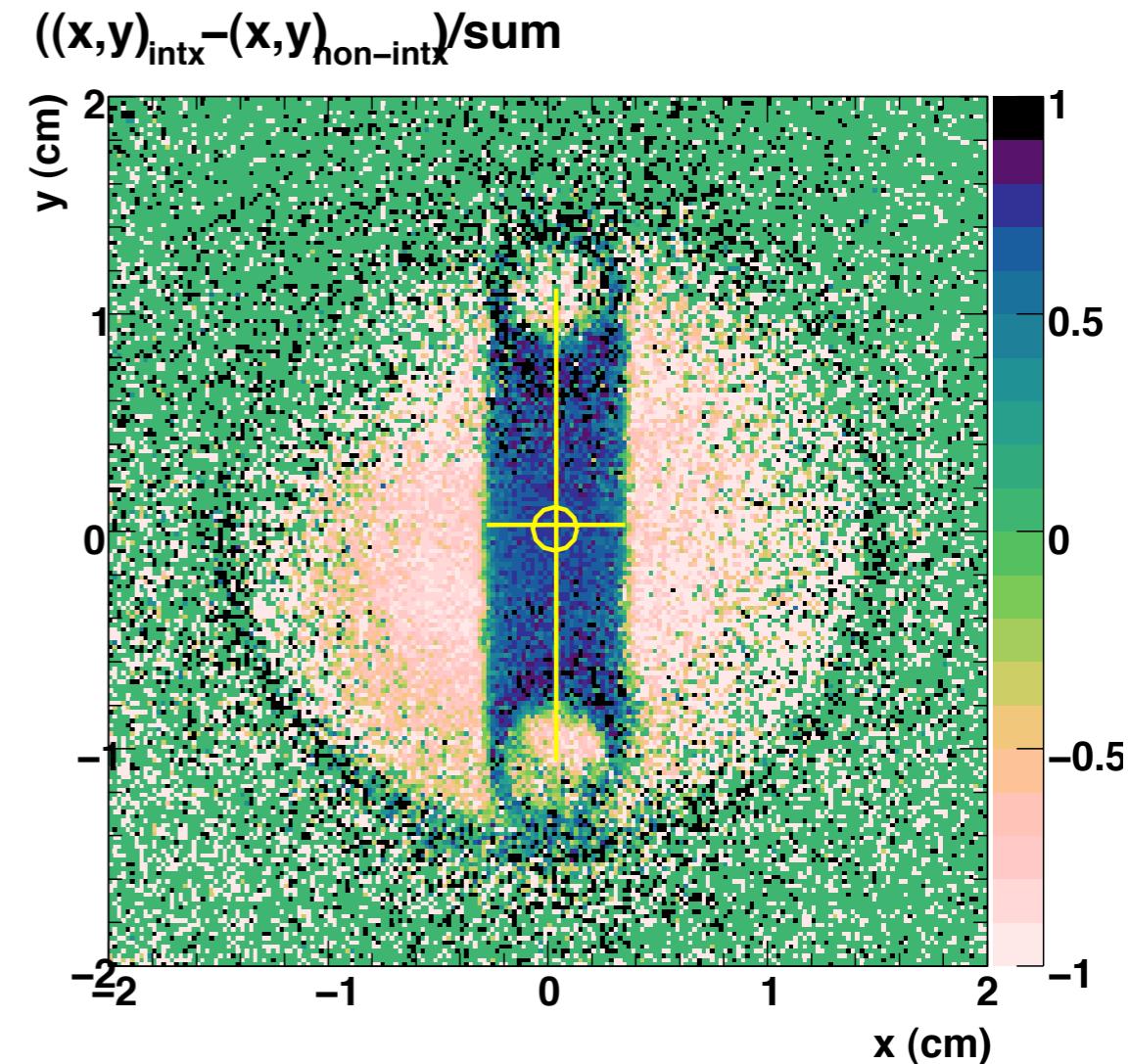
- Resolution is  $\sim 13\%$ .
- $\sim 4$  sigma e/had separation.



# Status of the Analyses

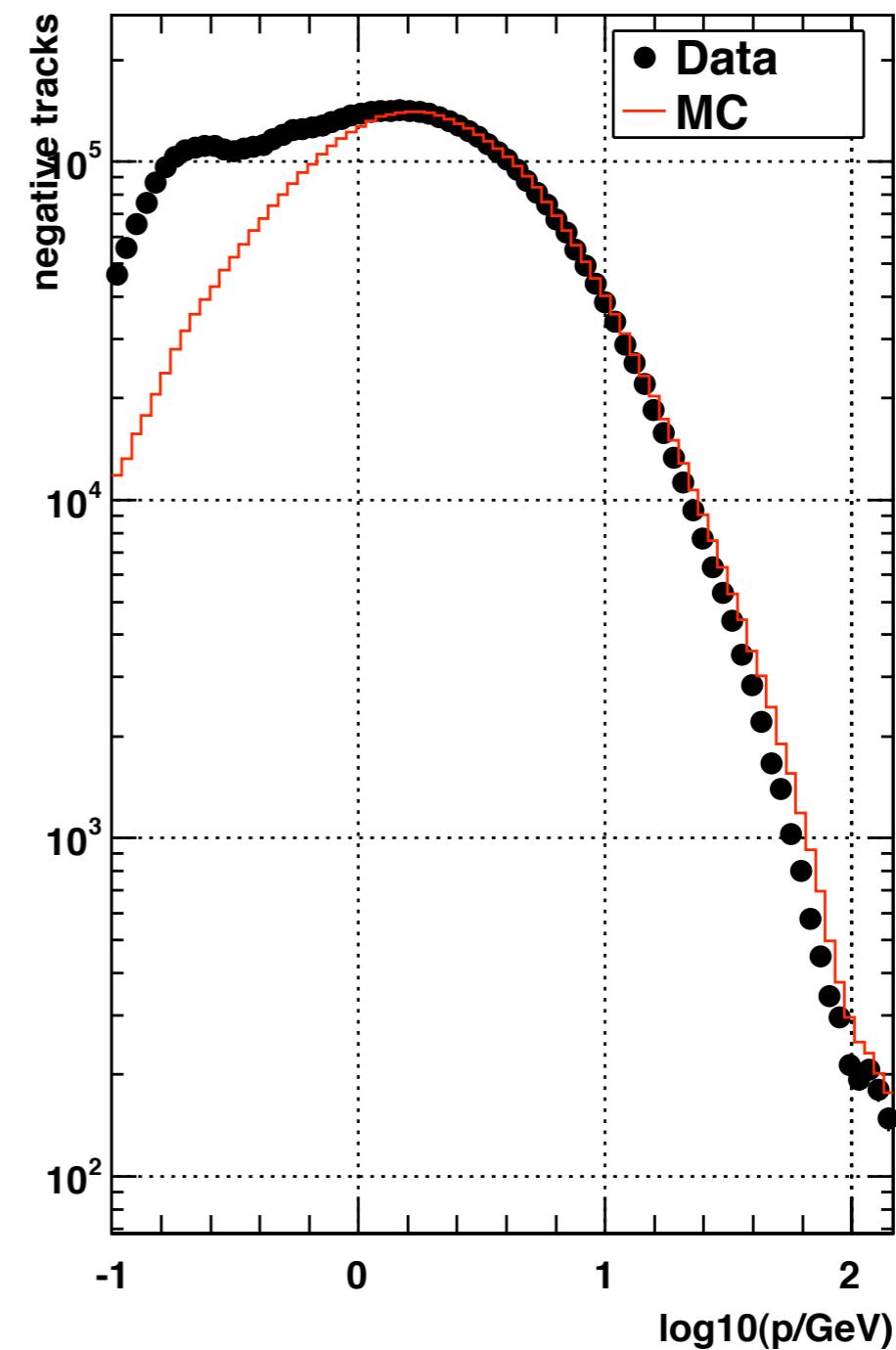
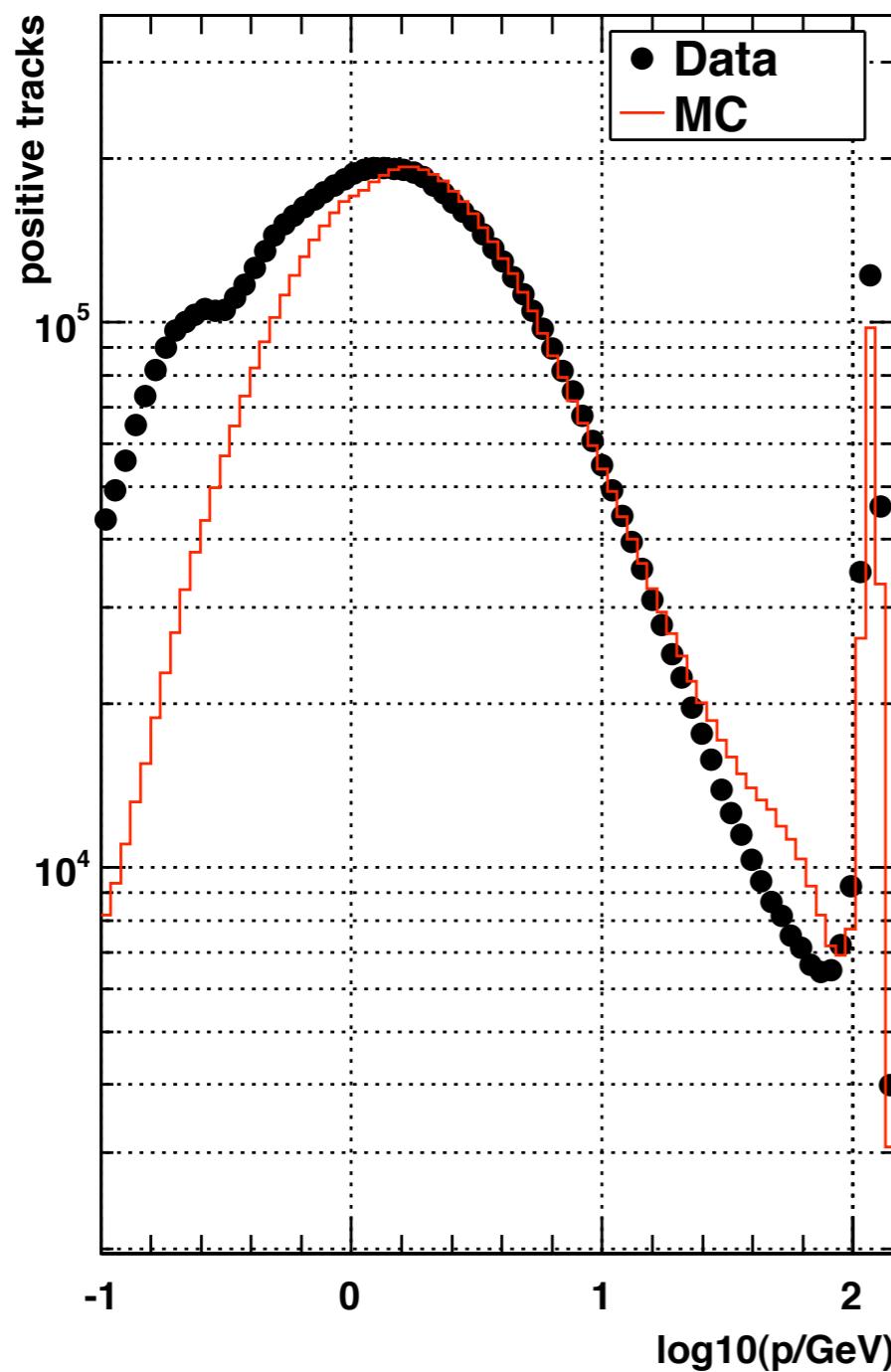
# NuMI Target Analysis

- MINOS adjusts their predicted ND neutrino energy spectra to agree with the measured spectra using  $(p_z, p_T)$ -dependent weights; these weights are an empirical fit, similar to the BPMT parameterization.
- The goal of this analysis is to provide similar weights to adjust the hadron production prediction off of the NuMI target with a direct measurement of the particle yields.

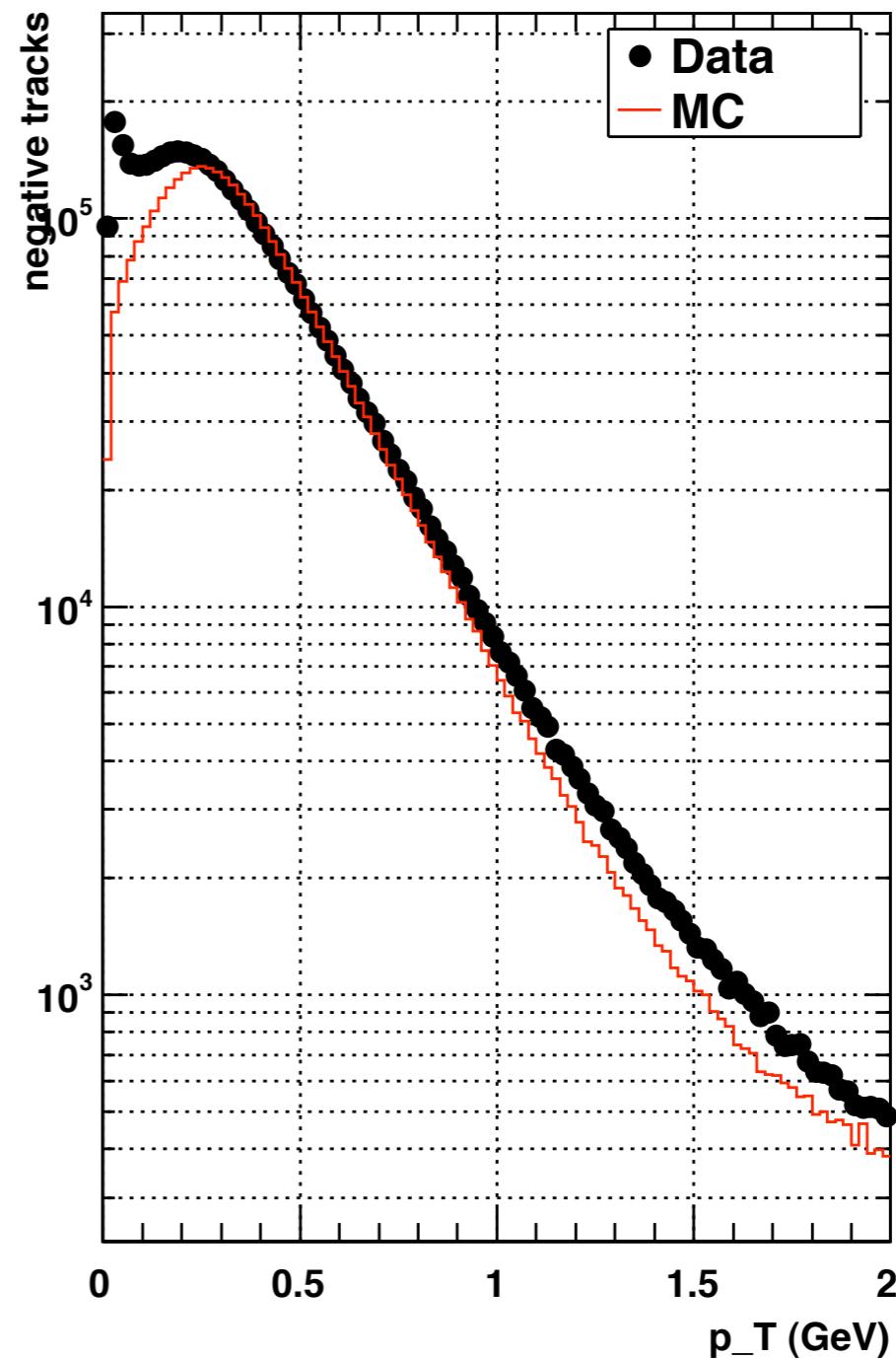
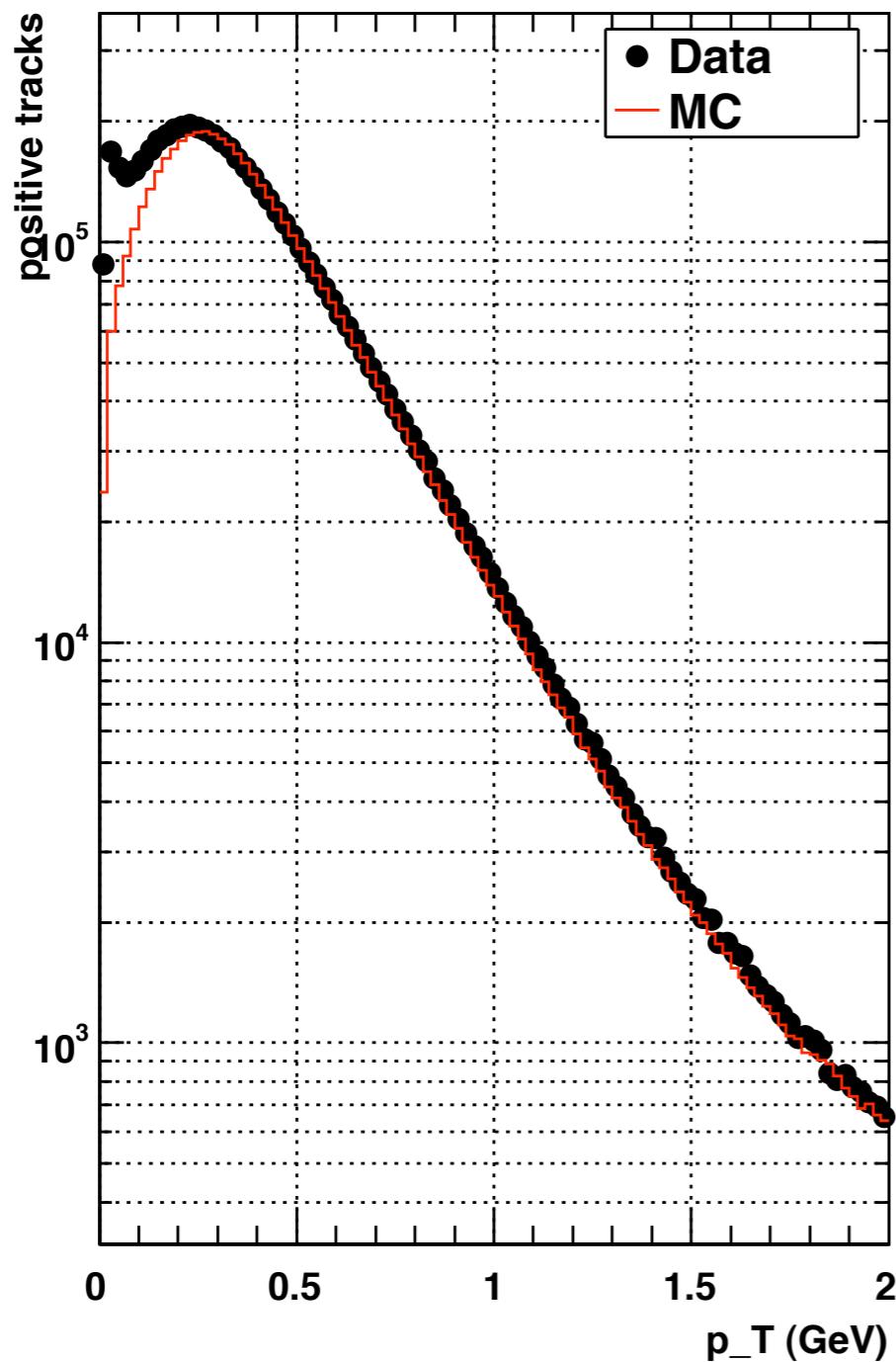


- The MIPP results will be particle yields, binned in  $(p_z, p_T)$ .

# Comparison of Data and MC $p_z$ Spectra

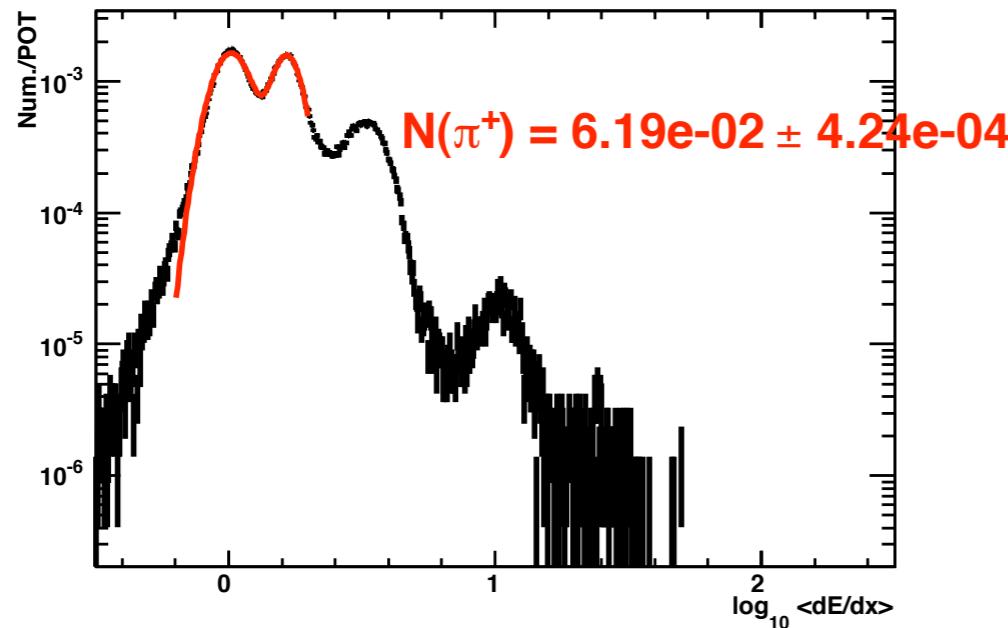


# Comparison of Data and MC $p_T$ Spectra

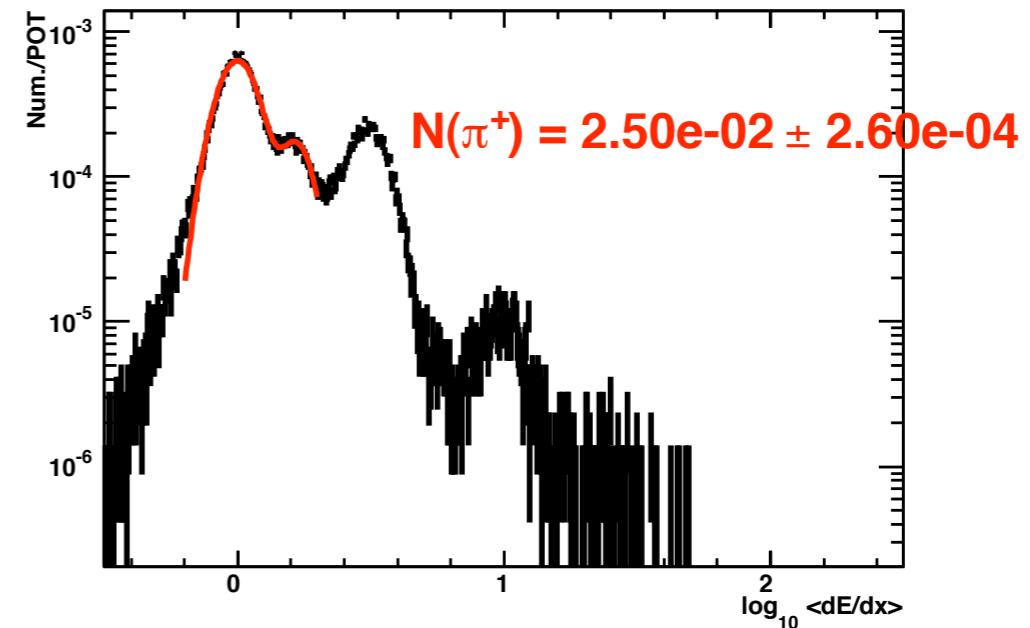


# Preliminary Pion Yield Measurement (TPC-only)

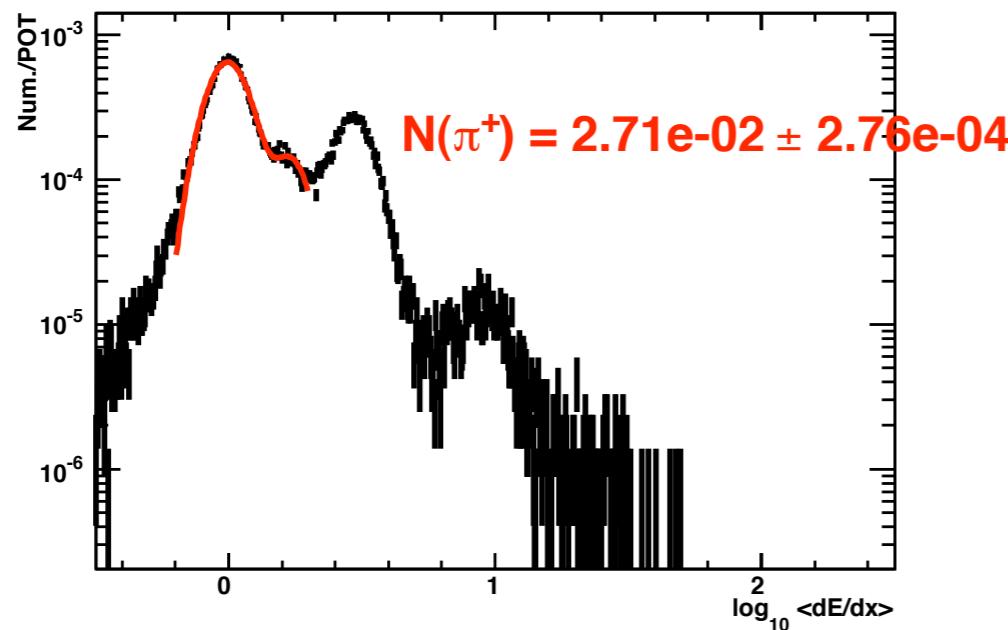
Data TPC  $\langle dE/dx \rangle$  Distribution,  $q > 0$ , Bin 15



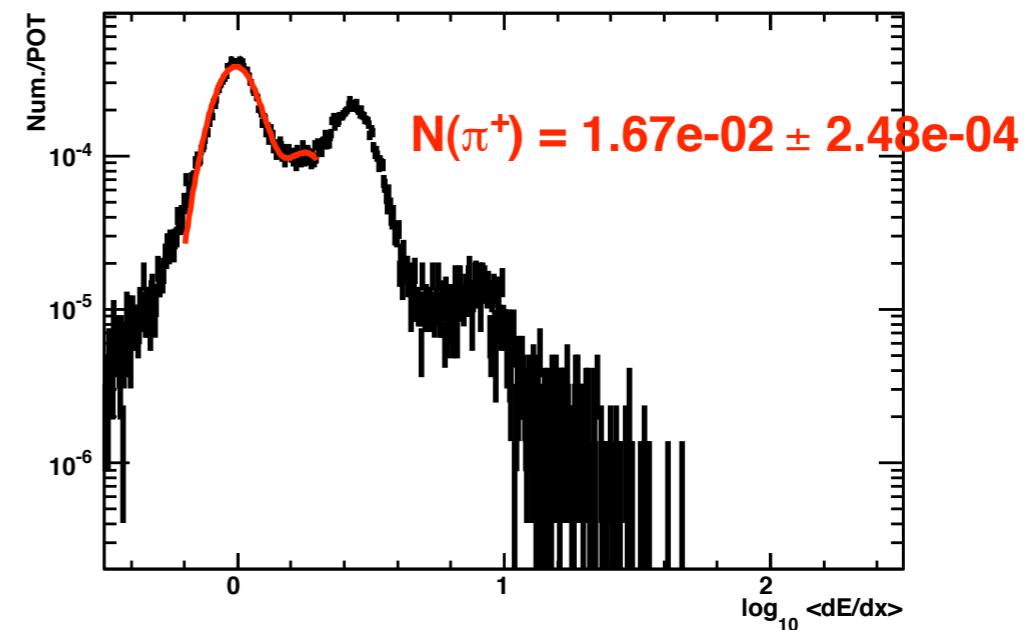
Data TPC  $\langle dE/dx \rangle$  Distribution,  $q > 0$ , Bin 16



Data TPC  $\langle dE/dx \rangle$  Distribution,  $q > 0$ , Bin 17

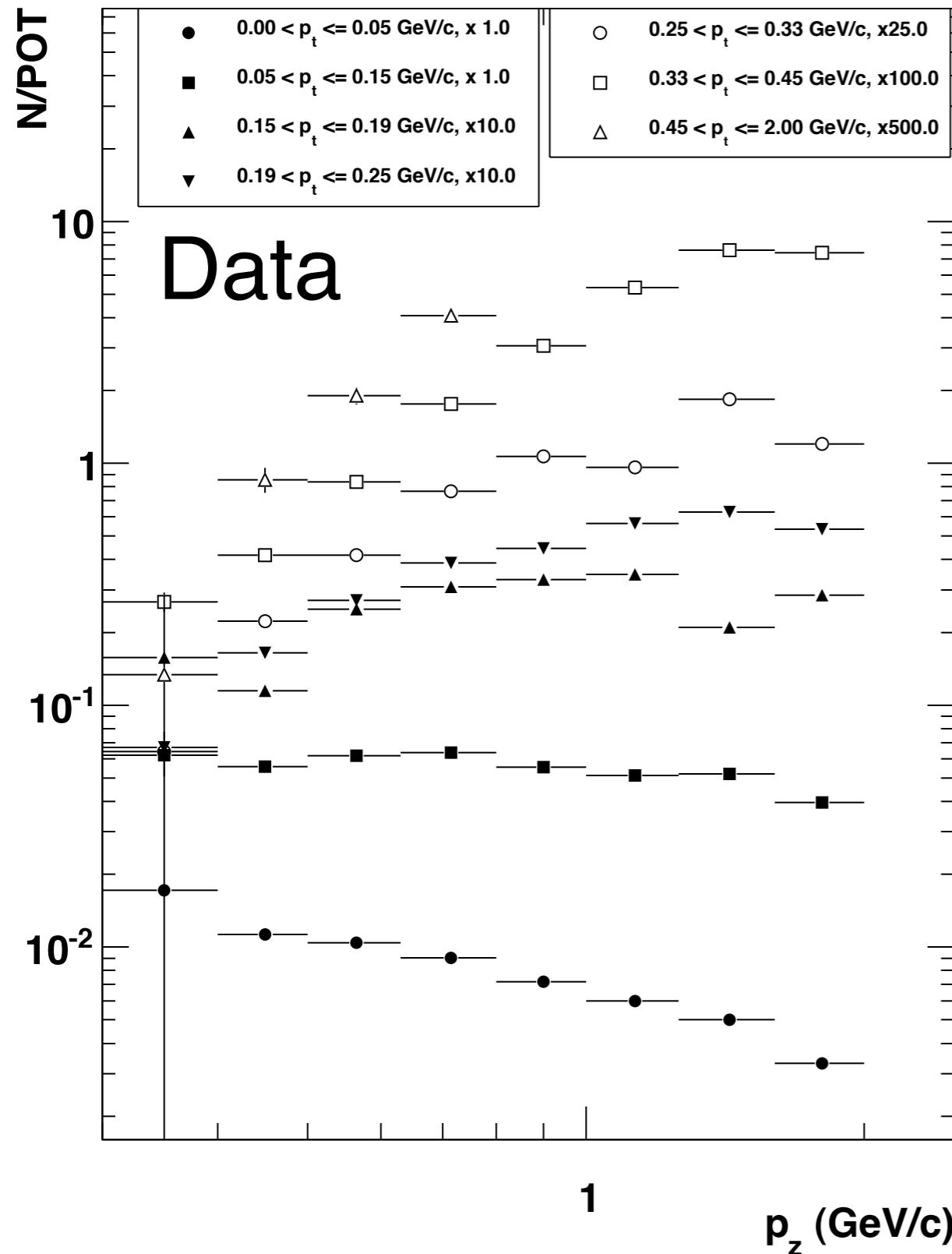


Data TPC  $\langle dE/dx \rangle$  Distribution,  $q > 0$ , Bin 18

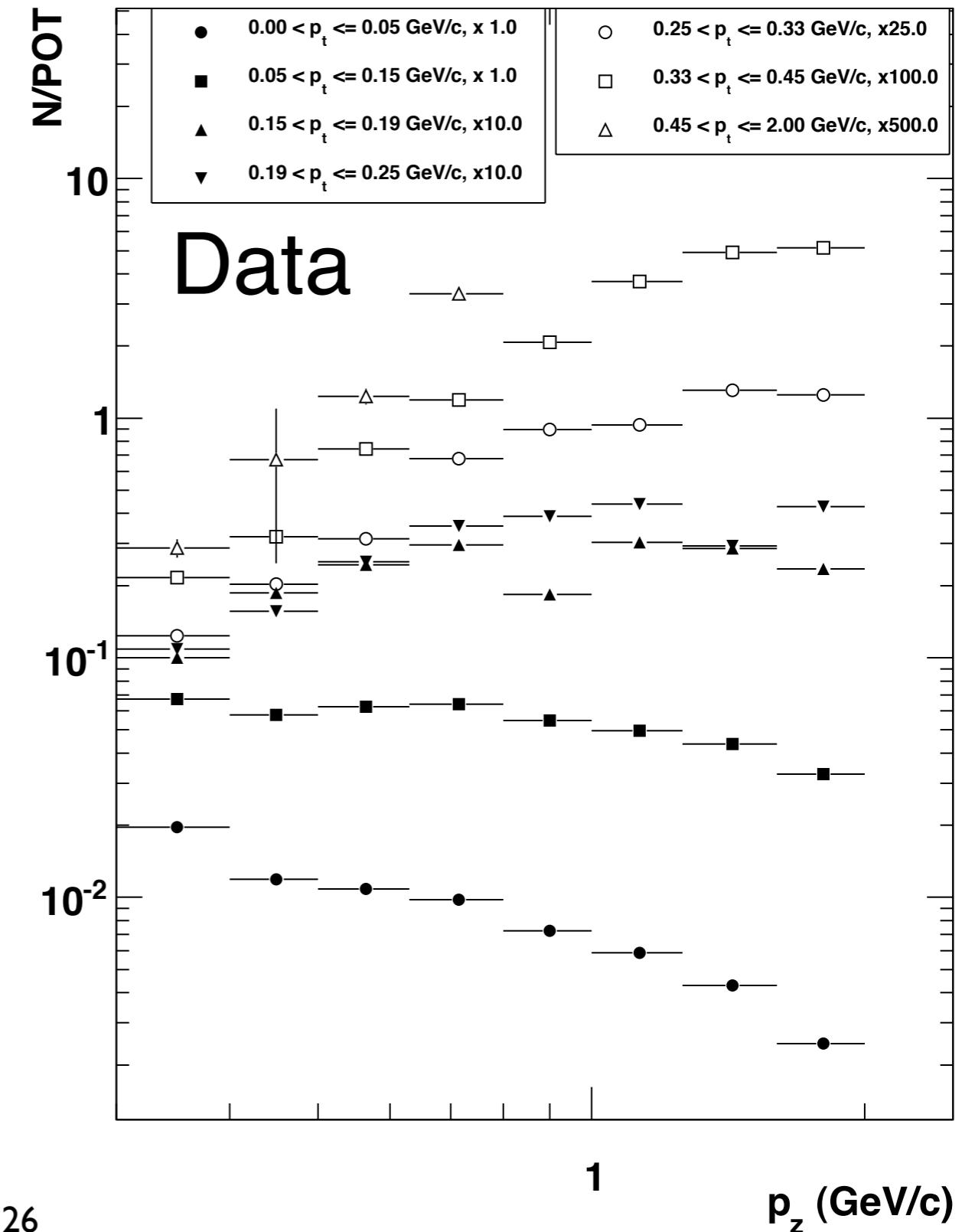


# Preliminary Pion Yield Measurement (TPC-only)

$N(\pi^+)/POT$  vs.  $p_z$

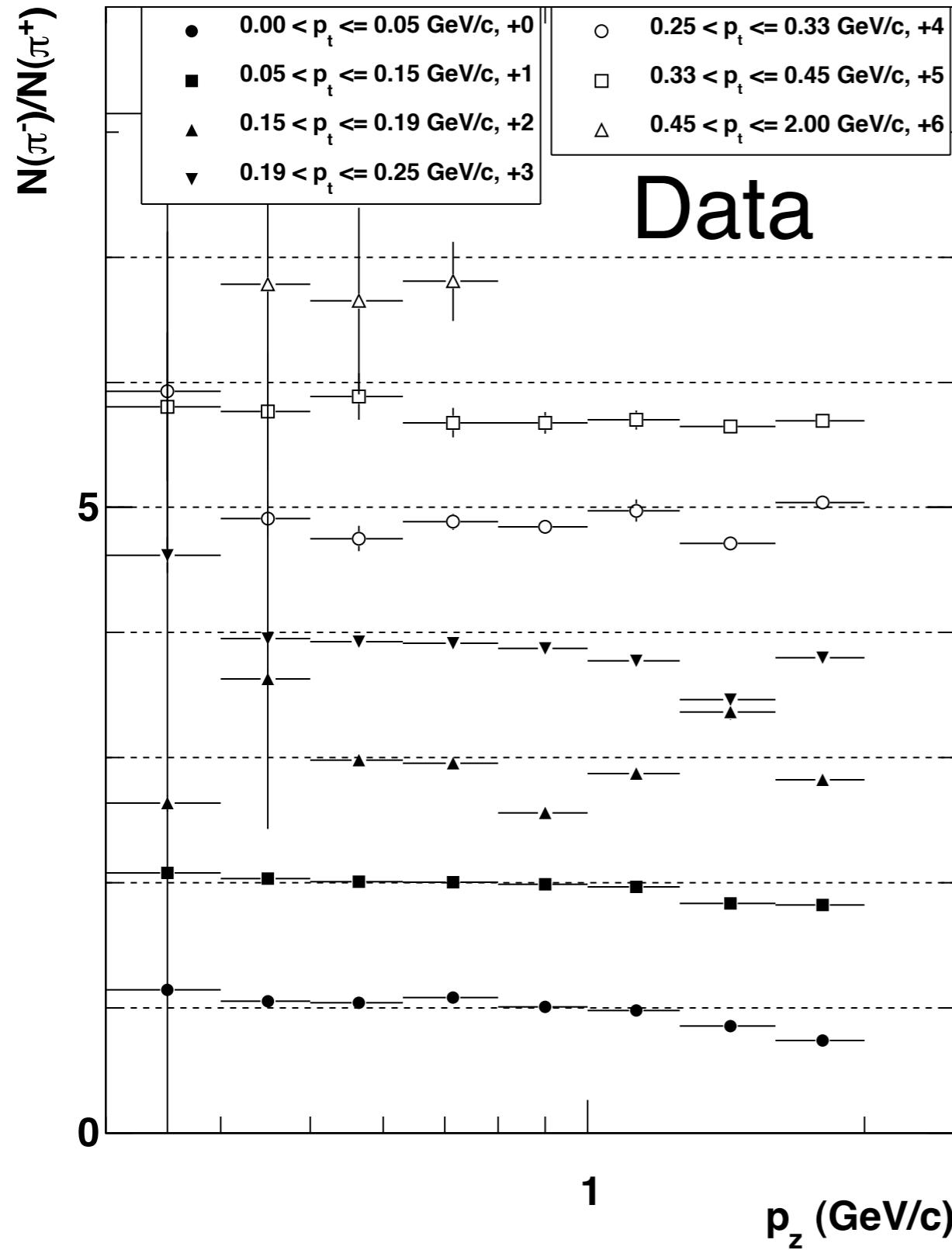


$N(\pi^-)/POT$  vs.  $p_z$

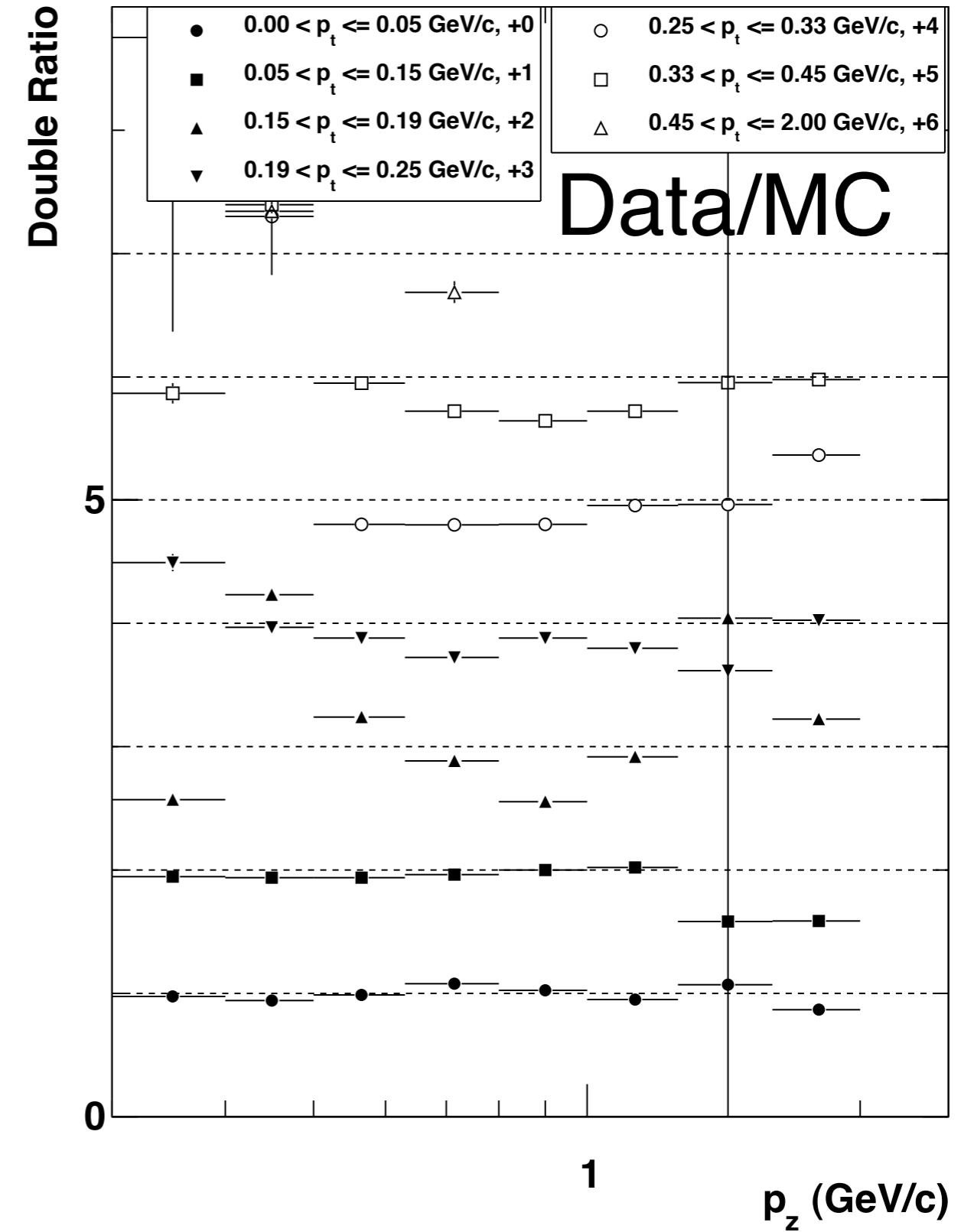


# Preliminary Pion Yield Measurement (TPC-only)

$N(\pi^-)/N(\pi^+)$  vs.  $p_z$



Data( $\pi^-/\pi^+$ )/MC( $\pi^-/\pi^+$ ) vs.  $p_z$



# NuMI Target Analysis Strategy

1. Adjust the MC so that the peaks and widths of the PID distributions agree with the Data.
2. Using the new MC PID distributions, we fit the MC to the Data to determine weights as a function of true ( $p_z, p_T$ ). The fit will take into account migrations from true to reconstructed  $p_z$ ,  $p_T$  and PID variables.
3. We next go back to the MC and the using the predetermined weights, calculate the true particle yields as a function of ( $p_z, p_T$ ).

Note: stage (1) is being refined, and the code to perform the fit in stage (2) is 90% complete.

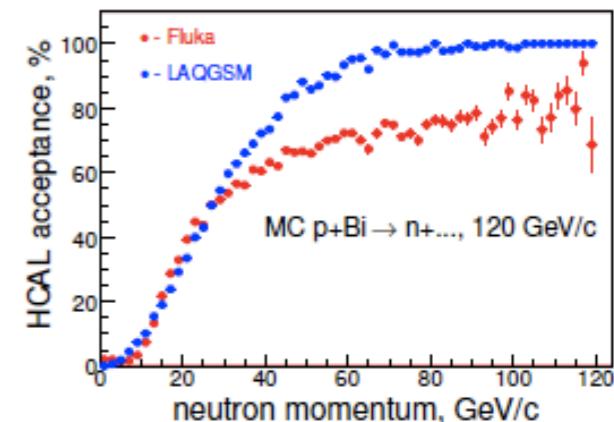
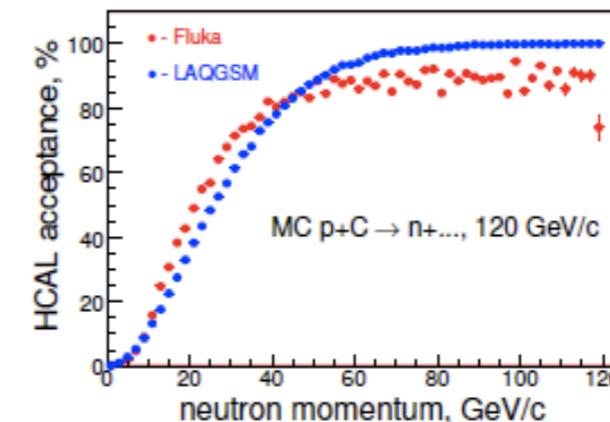
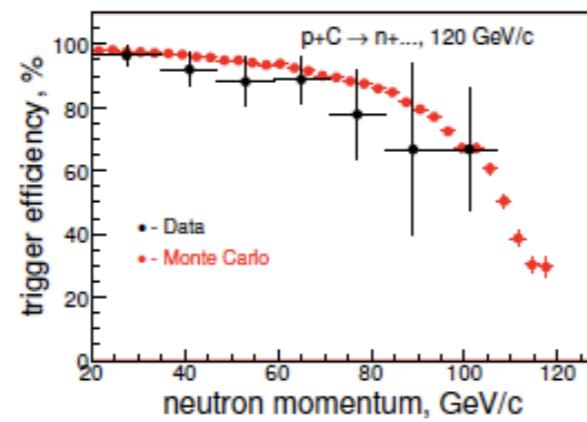
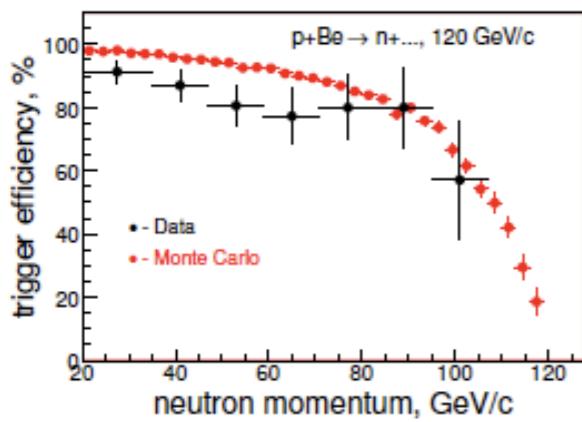
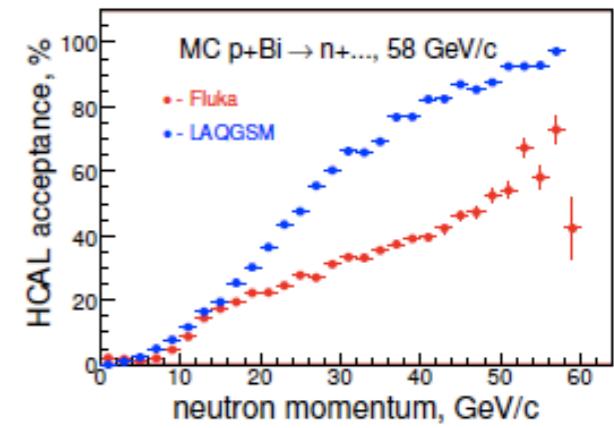
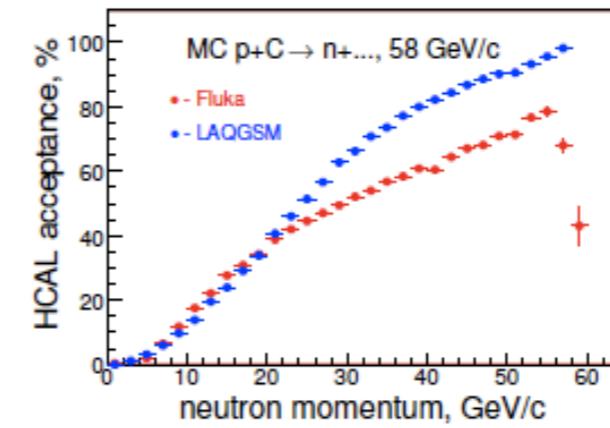
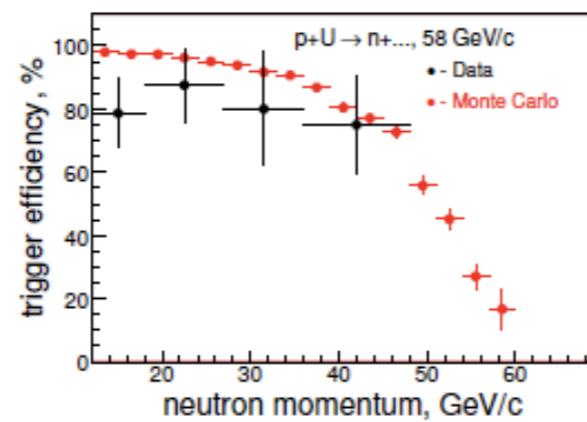
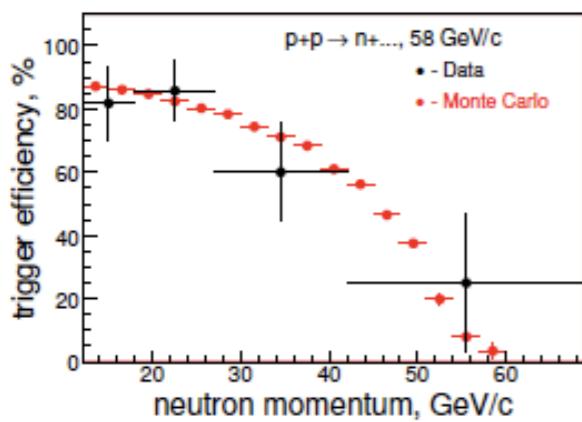
Time estimate for final results: 2-3 months.

# Forward Neutron Production Analysis

- The goal of this analysis is to determine neutron production cross-sections for a variety of beam momenta and targets.
- These data are important for tuning detector MC simulations and designs for future calorimeters.
- This analysis makes use of the downstream EM and Hadron calorimeters;  $\theta_n(\text{max}) \approx 23 \text{ mrad}$ .

# Forward Neutron Production Analysis

$$\sigma_n \sim \frac{N_n(t_{in}) - N_n(t_{out})}{N_{beam}} \times \frac{1}{An_t}$$



- Trigger efficiency and calorimeter acceptance need to be resolved.
- Other than that, basically waiting for MC data sets.
- Time estimate for completion: 2-3 months.

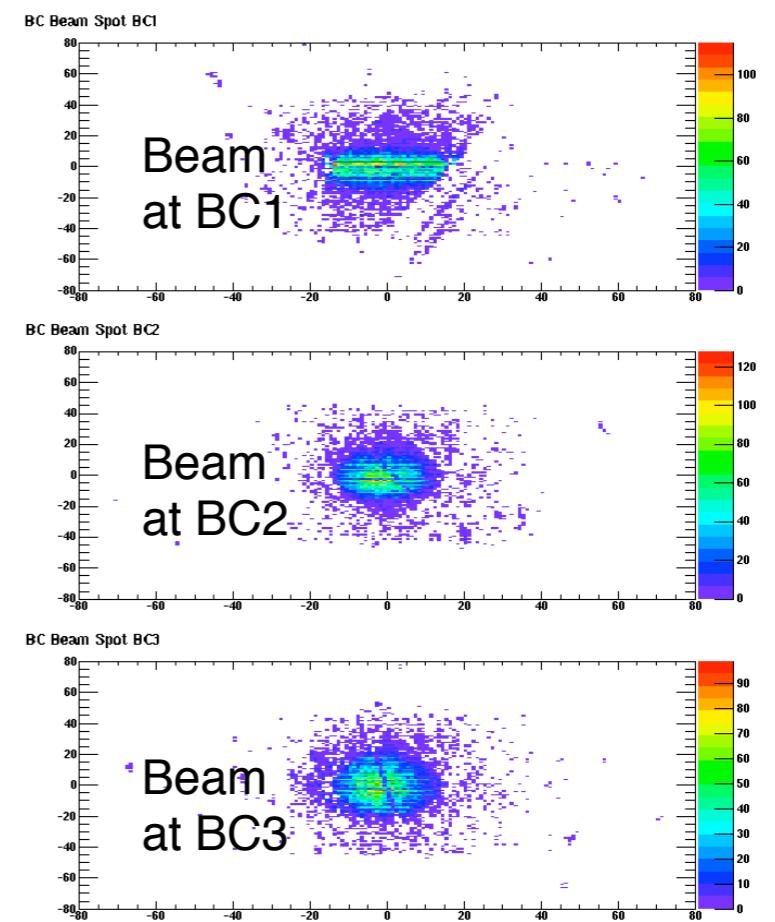
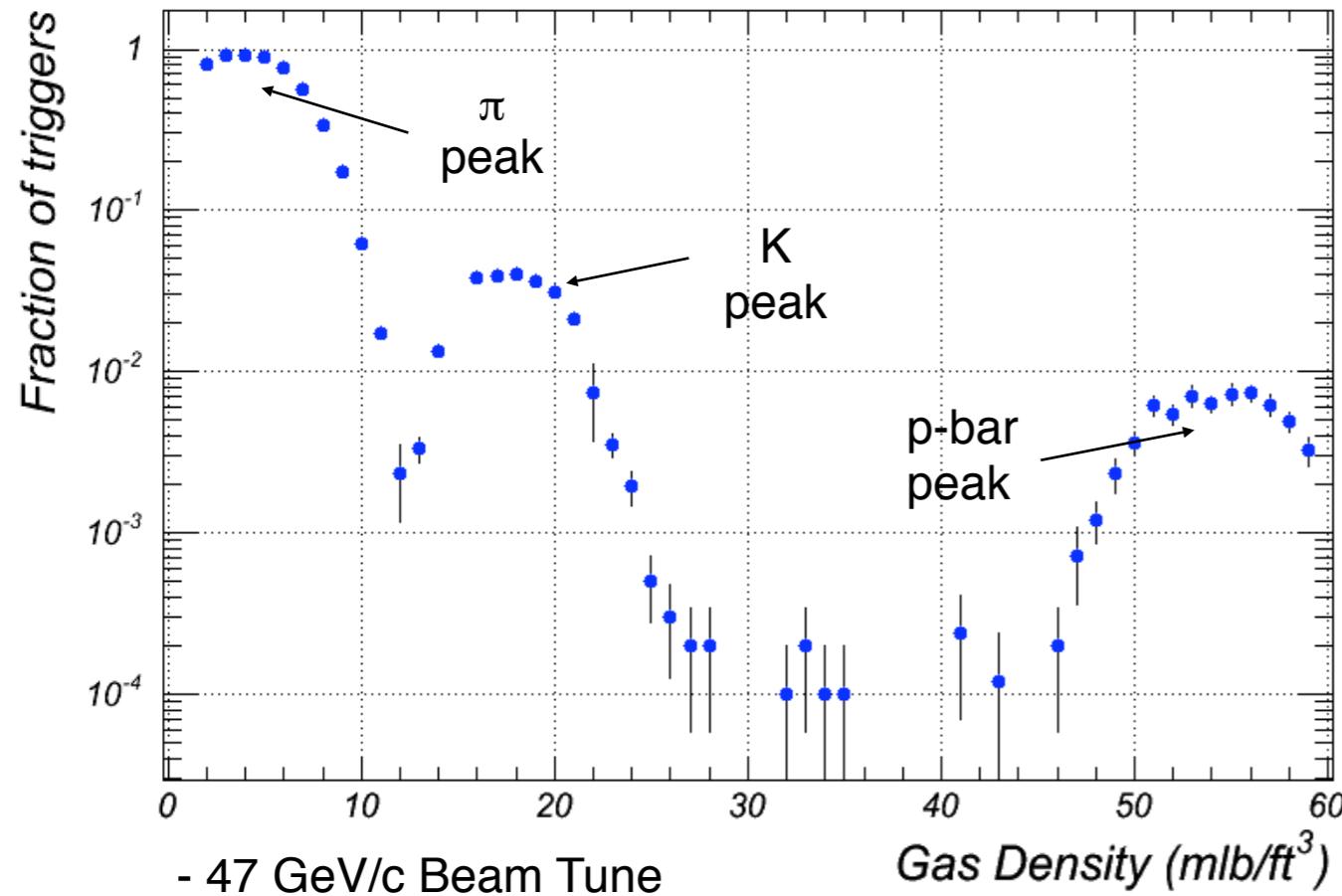
# Conclusions

- MIPP has collected several millions of events of  $\pi$ ,  $K$  and  $p$  beams at various momenta incident on various targets.
- MIPP collected  $1.6 \times 10^6$  POT events using the NuMI target, the analysis of which is the collaboration's highest priority, although other analyses are on-going.
- All MIPP sub-detector systems have been calibrated and the MC tuned to the data. MC/Data PID agreement looks reasonable, but likely will have to be tuned offline.
- Time scale for both the NuMI target and forward neutron production analyses is ~2-3 months.

# Backup Slides

# The MIPP Beamline

Downstream Beam Cherenkov in  $\times \overline{\text{out}}$

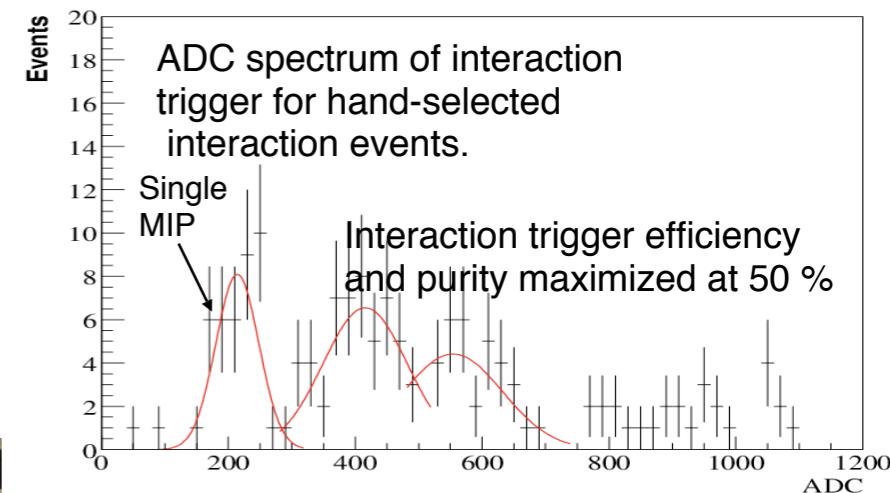
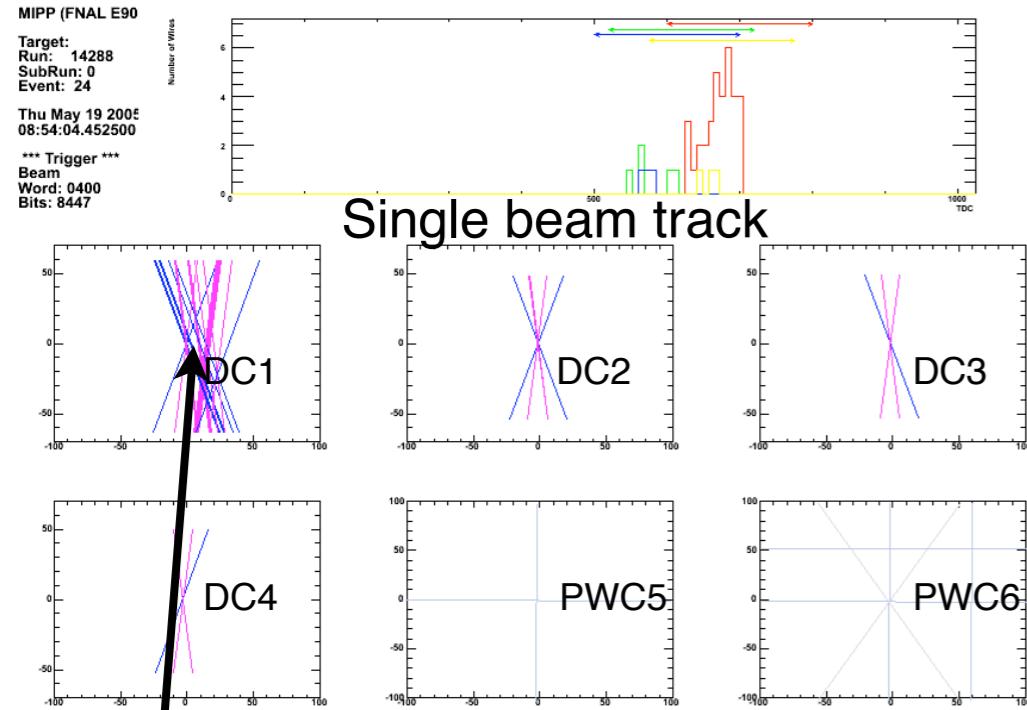


Thu Apr 28 17:56:09 2005

Run 13855:2

- Protons from the Main Injector strike a secondary target upstream of the MIPP spectrometer, producing secondary  $\pi$ 's, K's and p's.
- A series of magnets allow momentum selection from 5-85 GeV; two Ckov detectors upstream of the MIPP targets are used to identify the incoming particle.
- Three wire chambers upstream of the target are used to measure the trajectory of the incoming particle.

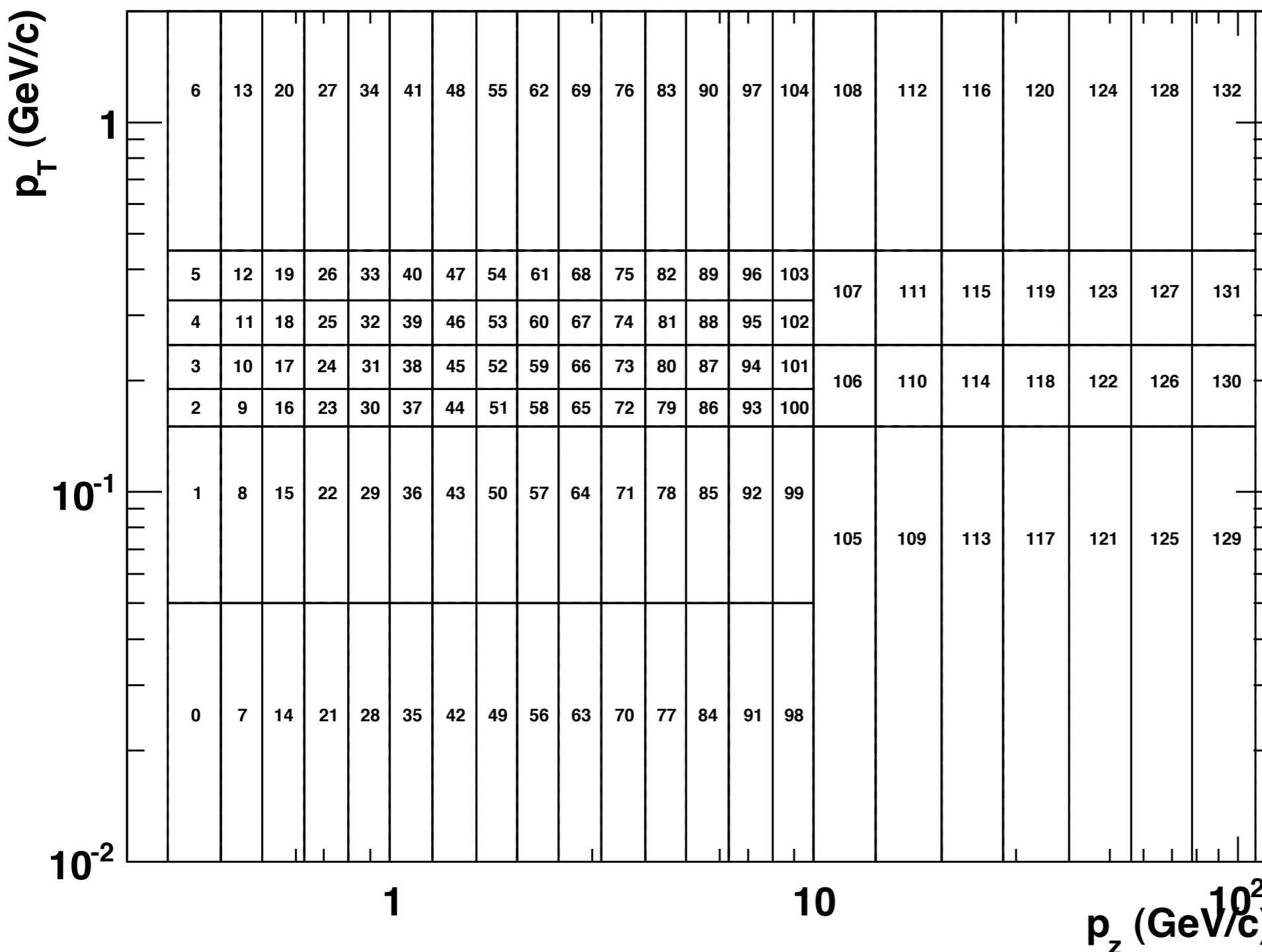
# The MIIPP Interaction Trigger



- DAQ rate is low ( $\sim 30$  Hz), so we enhance our sample of interaction events using a track multiplicity trigger.
- Original interaction trigger was based on multiplicity in 1st drift chamber upstream of target. However, noise in this chamber and beam halo resulted in a very large number of false positives.
- Early on in the experiment, an interaction trigger was formed from a combination of a thin piece of scintillator and spare MINOS parts (optical fibers and connectors).

# Preliminary ( $p_z, p_T$ ) Bins for NuMI Analysis

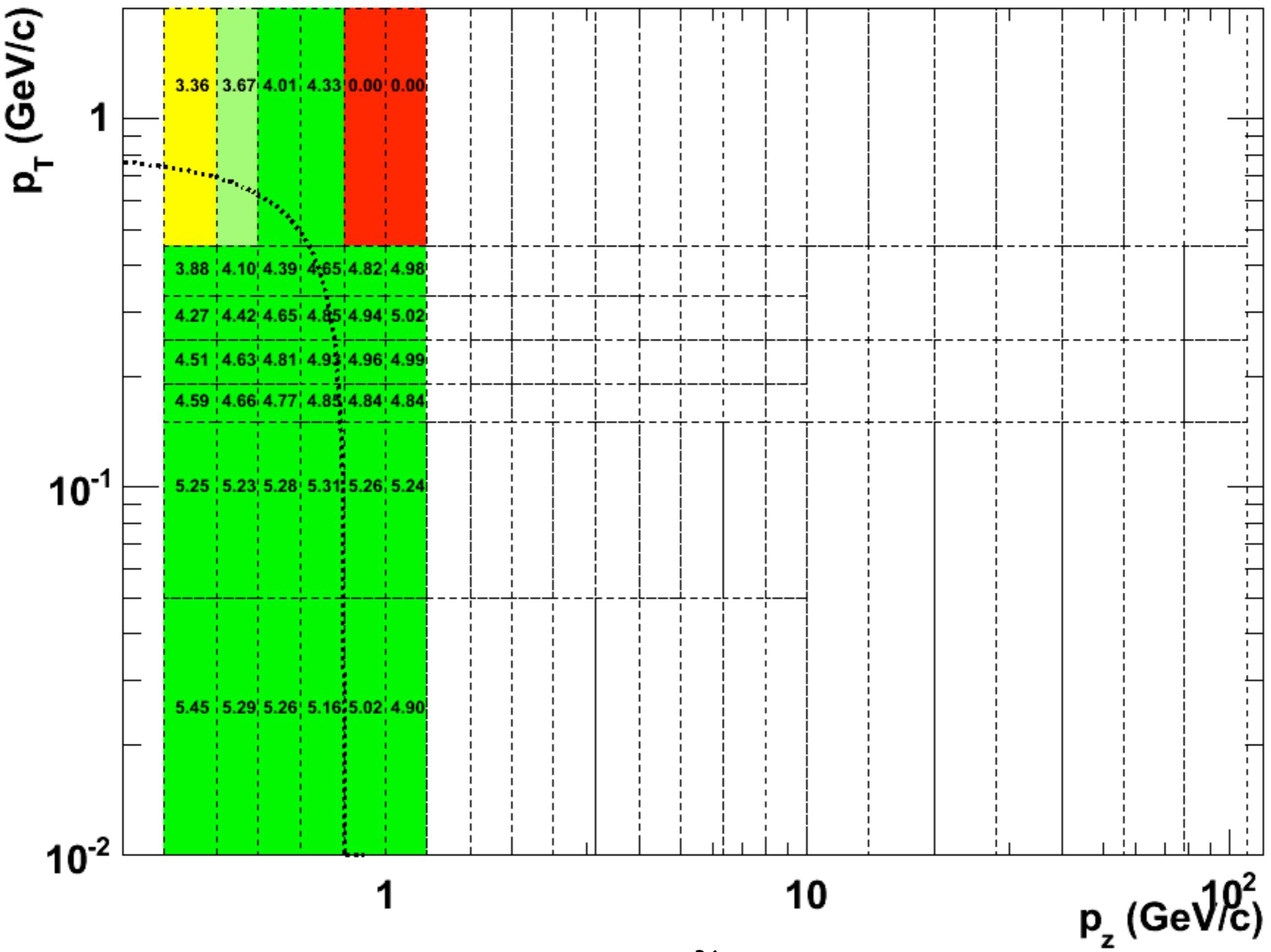
## Bin Numbers vs. ( $p_z, p_T$ )



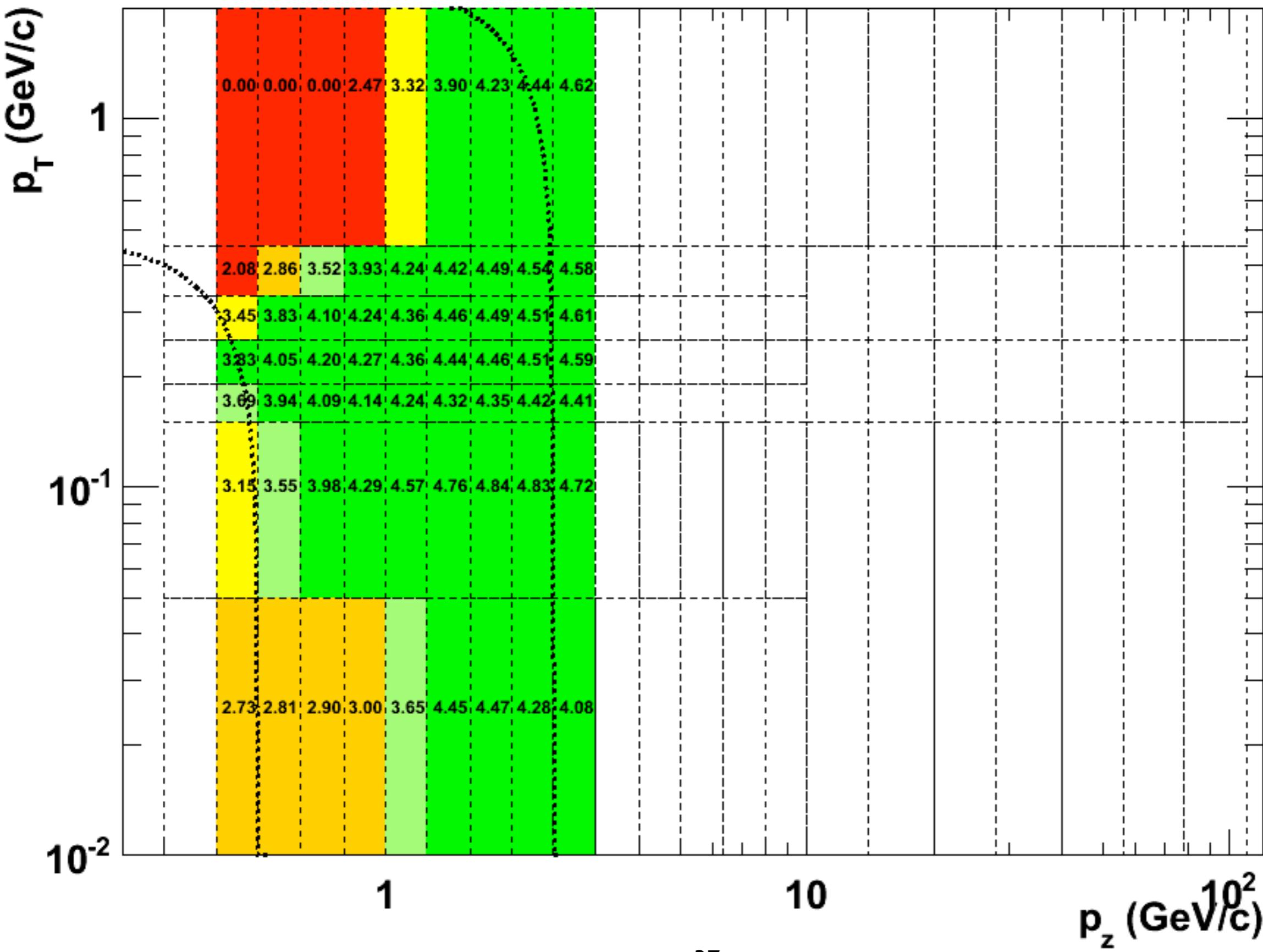
Bins are selected based on statistics and simplification of migration matrix (from true to reco)

Require  $< \sim 3\%$  statistical uncertainty on number of positive tracks.

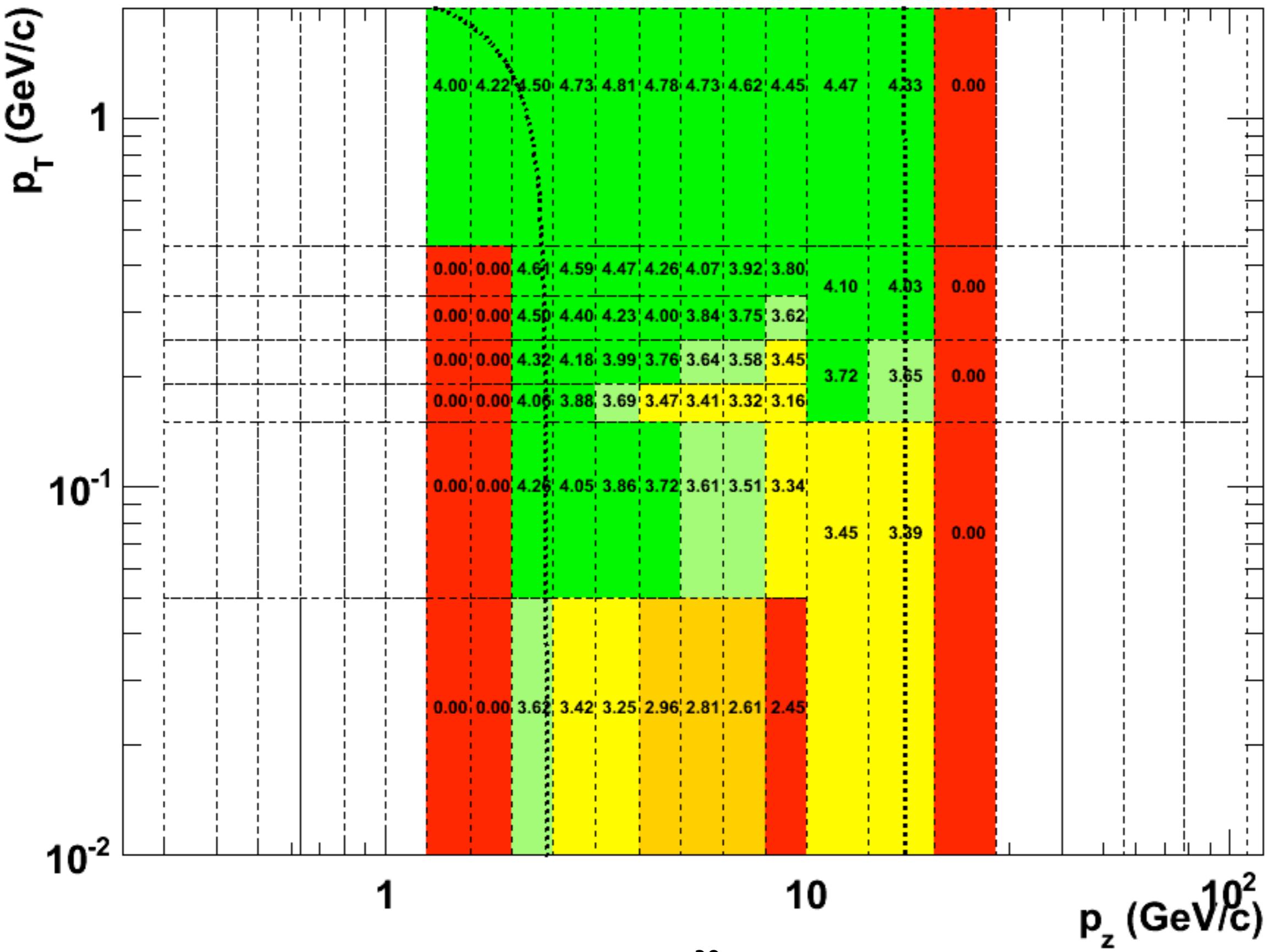
# Total Number of Clean TPC Tracks    z-axis = $\log_{10}(N)$



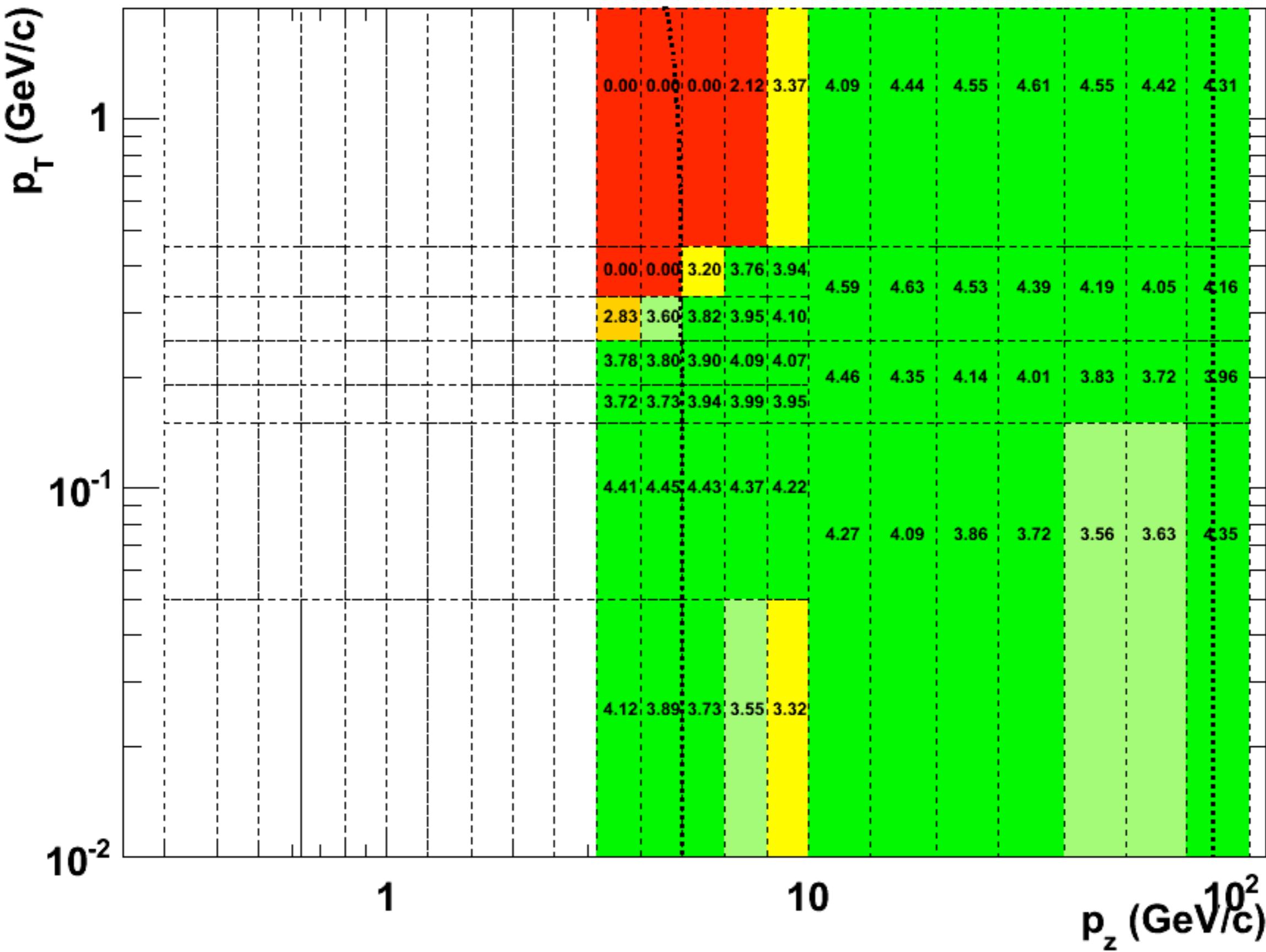
# Total Number of Clean ToF Tracks    z-axis = $\log_{10}(N)$



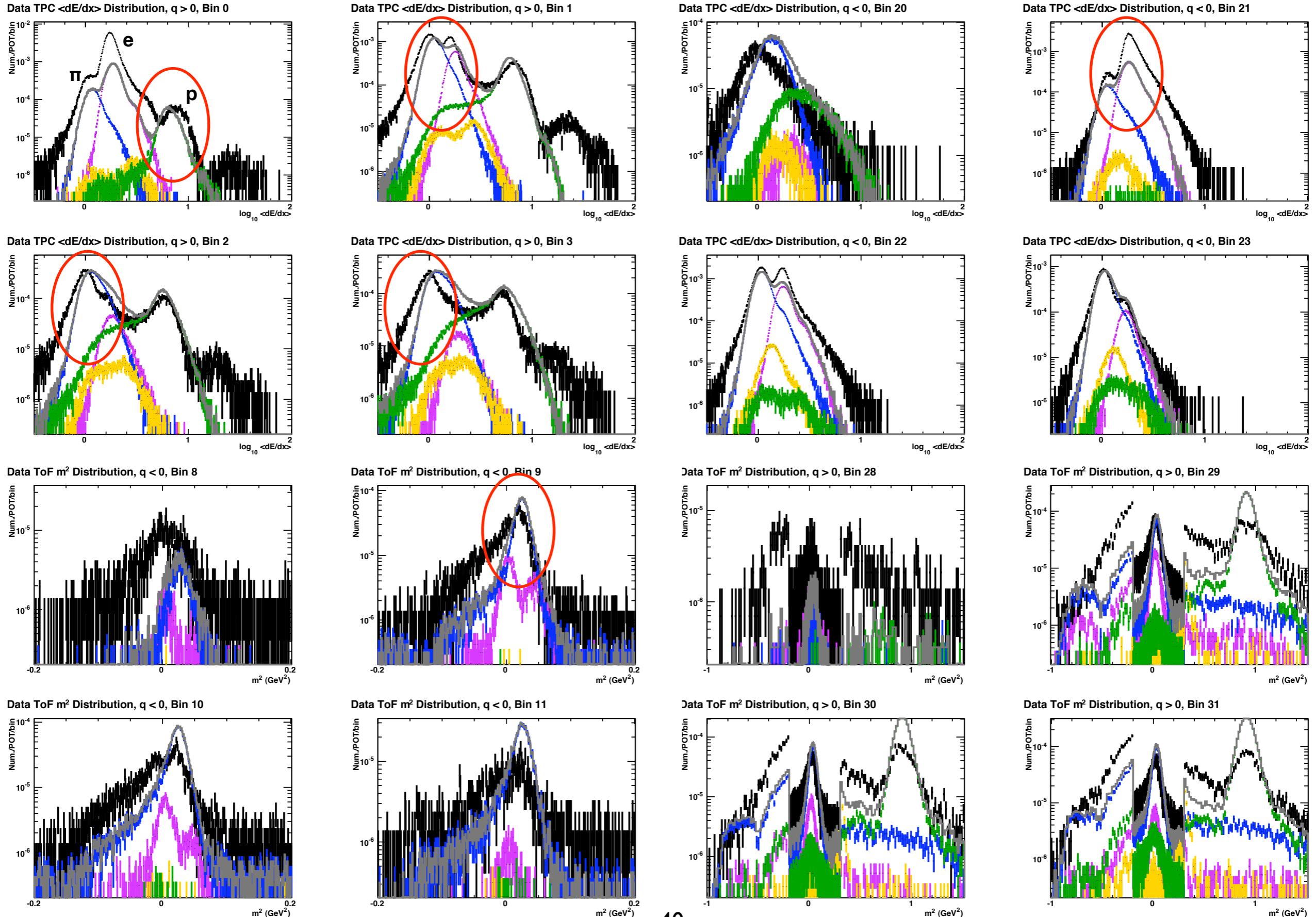
# Total Number of Clean Ckov Tracks z-axis = $\log_{10}(N)$



# Total Number of Clean RICH Tracks z-axis = $\log_{10}(N)$

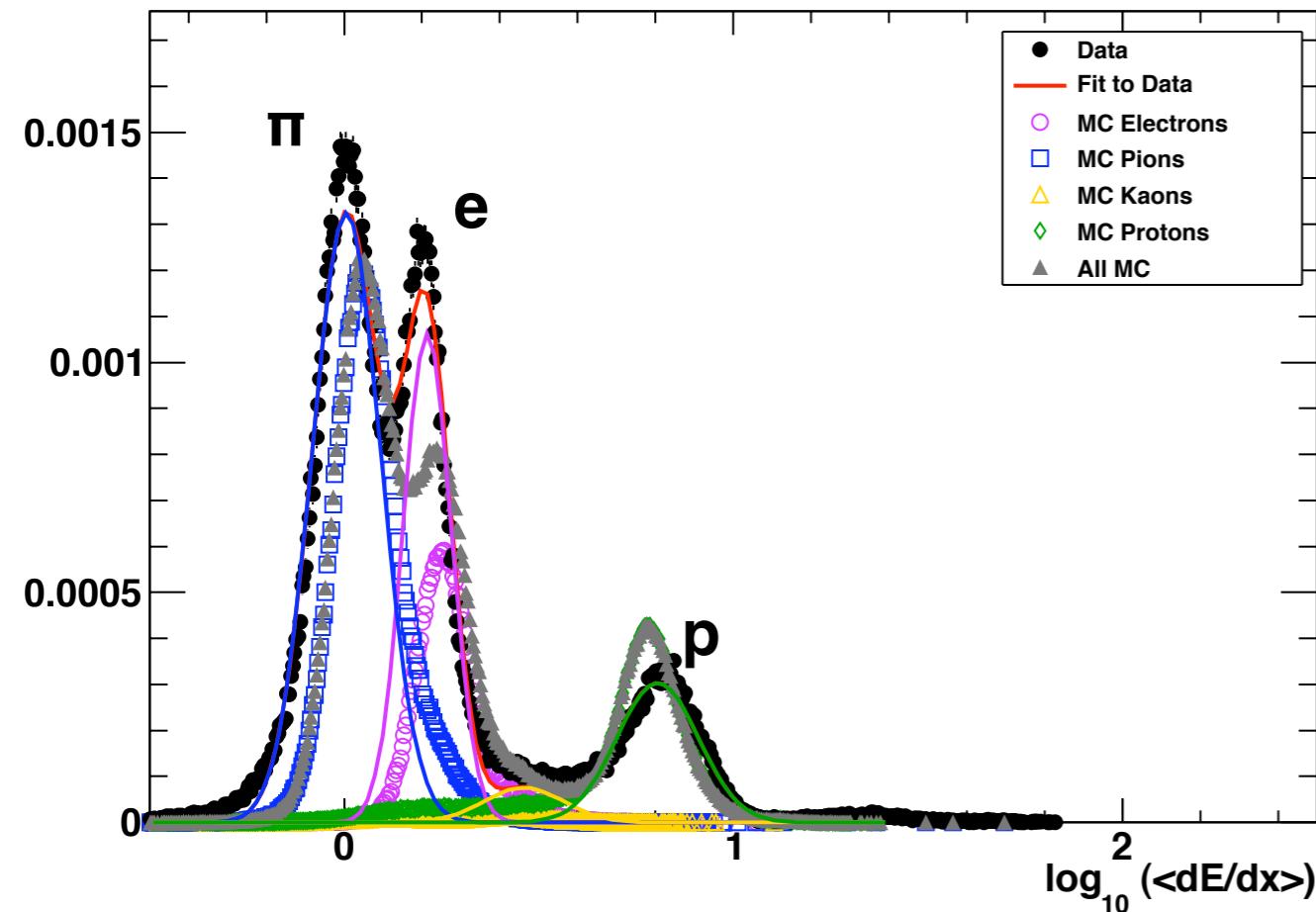


# Data/MC Comparisons - Why We Need to Tune

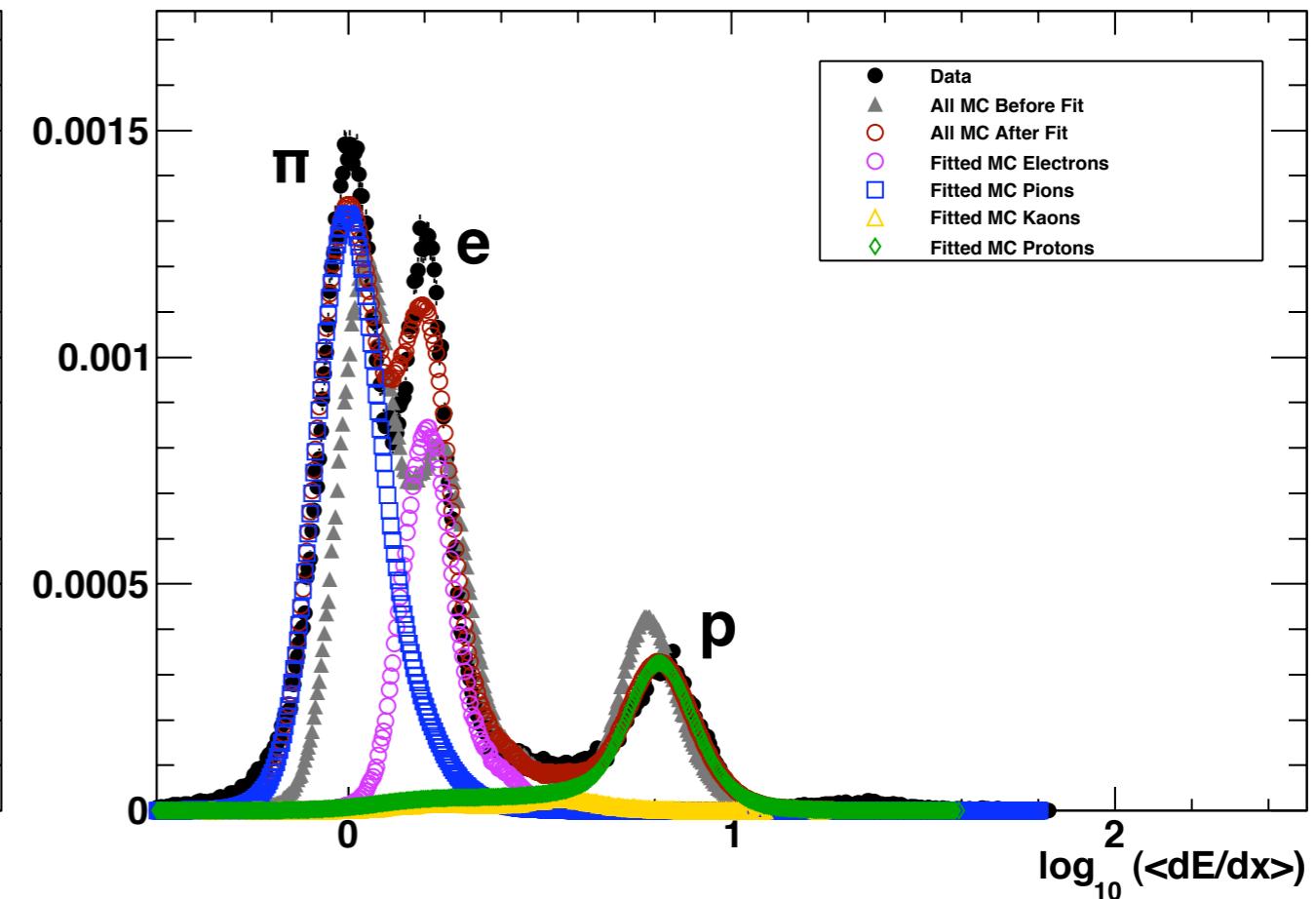


# Preliminary Fits of MC to Data

TPC  $\log_{10}(\langle dE/dx \rangle)$ ,  $q > 0$ , Bin 1 (0.30,0.05)-(0.40,0.15)

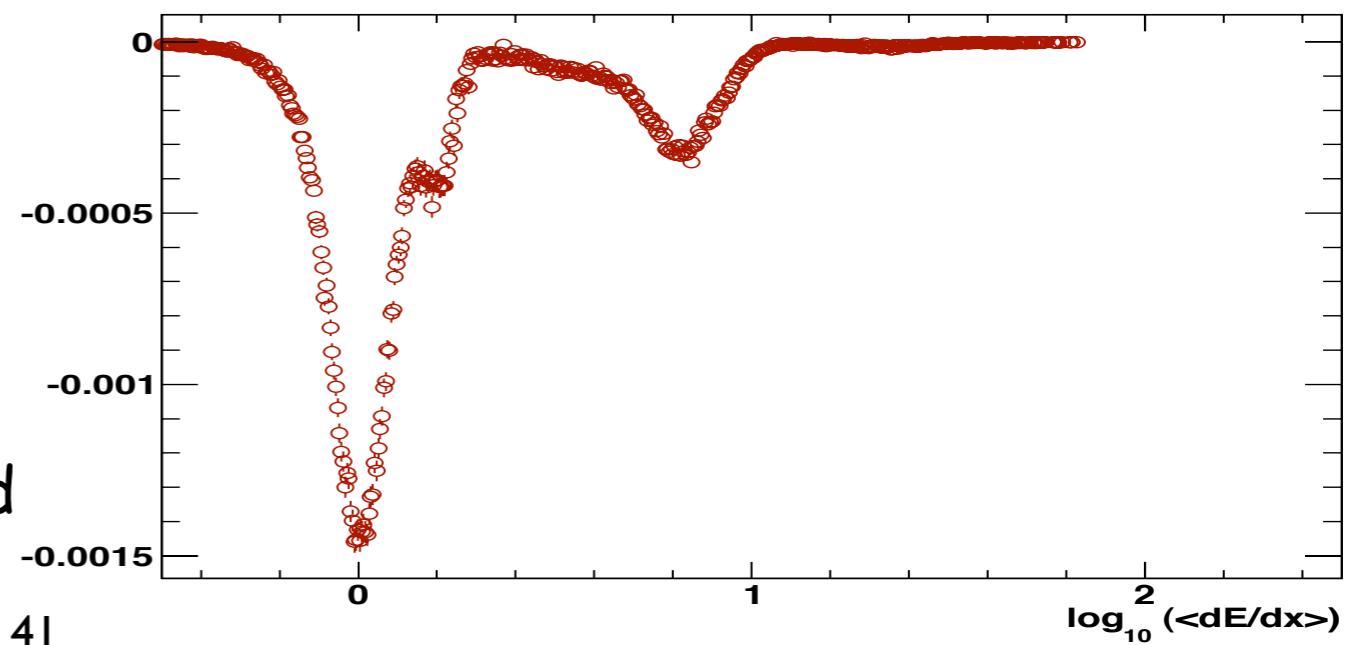


TPC  $\log_{10}(\langle dE/dx \rangle)$ ,  $q > 0$ , Bin 1 (0.30,0.05)-(0.40,0.15)



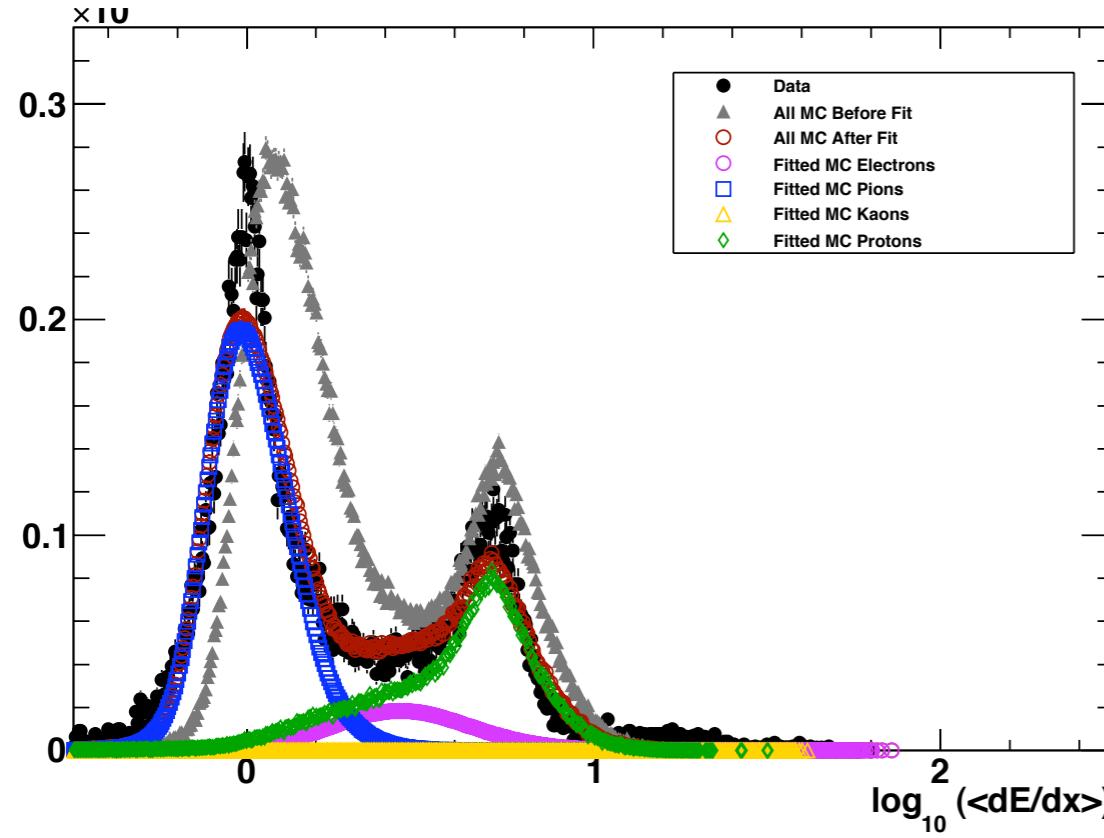
- 12-parameter fit, 3 parameters for each PID ( $e, \pi, K, p$ ):
  - 1 parameter to shift PID dist.
  - 1 parameter to broaden PID dist.
  - 1 parameter to scale PID dist.
- Fit works reasonably well, but some PID distributions need to be more narrow, and scaling doesn't quite come out right.

TPC Fit Residuals,  $q > 0$ , Bin 1



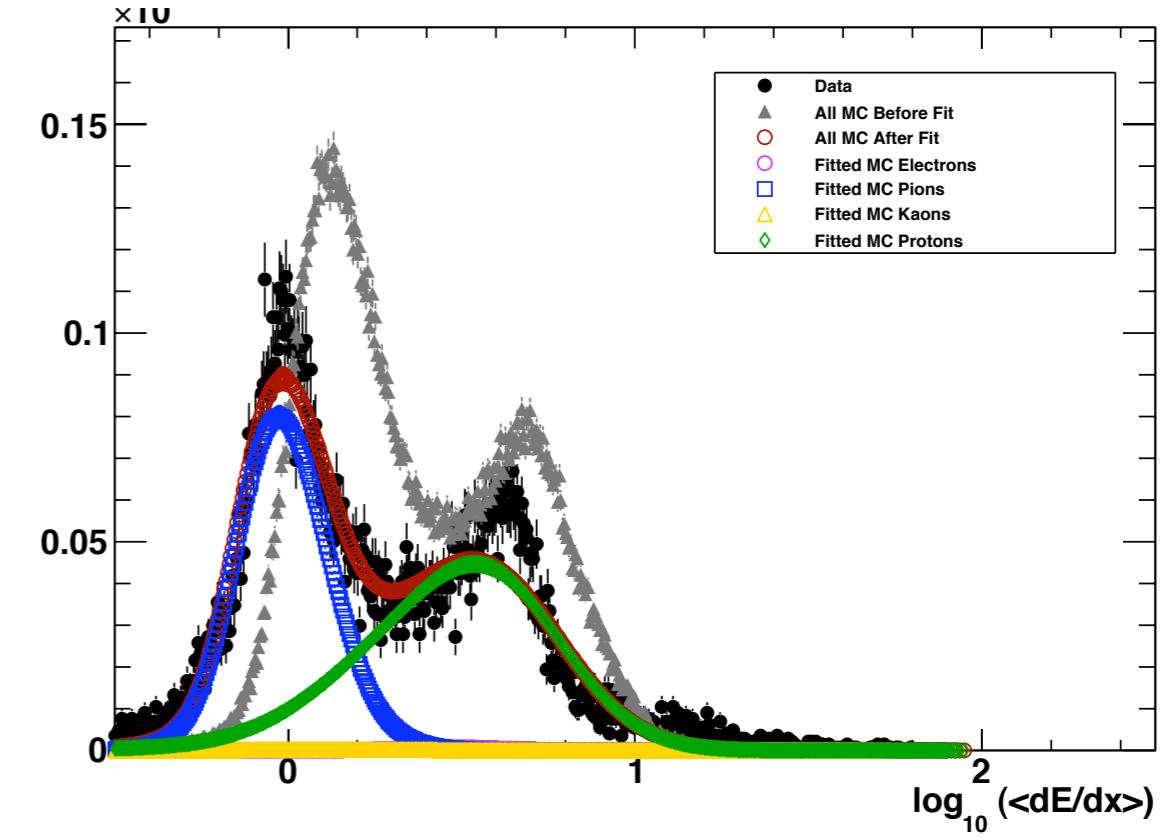
# More Preliminary Fits of MC to Data

TPC  $\log_{10}(\langle dE/dx \rangle)$ ,  $q > 0$ , Bin 3 (0.30,0.19)-(0.40,0.25)

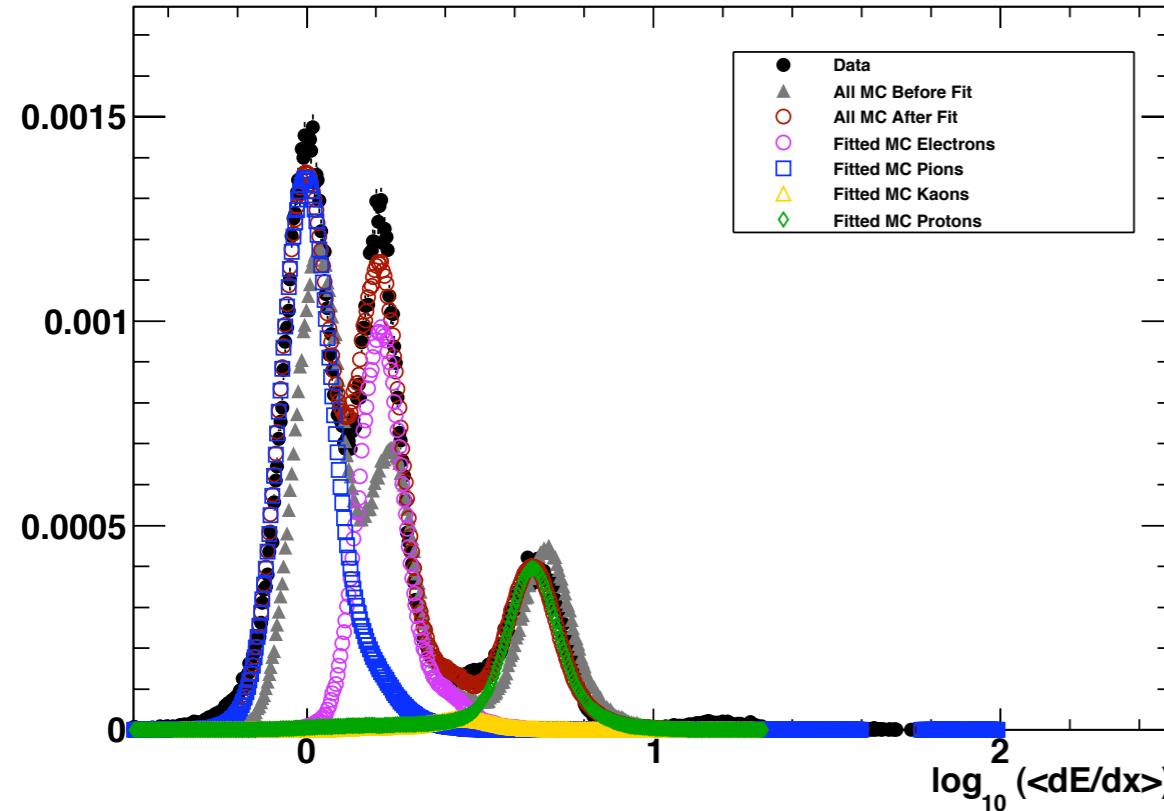


TPC  $\log_{10}(\langle dE/dx \rangle)$ ,  $q > 0$ , Bin 4 (0.30,0.25)-(0.40,0.33)

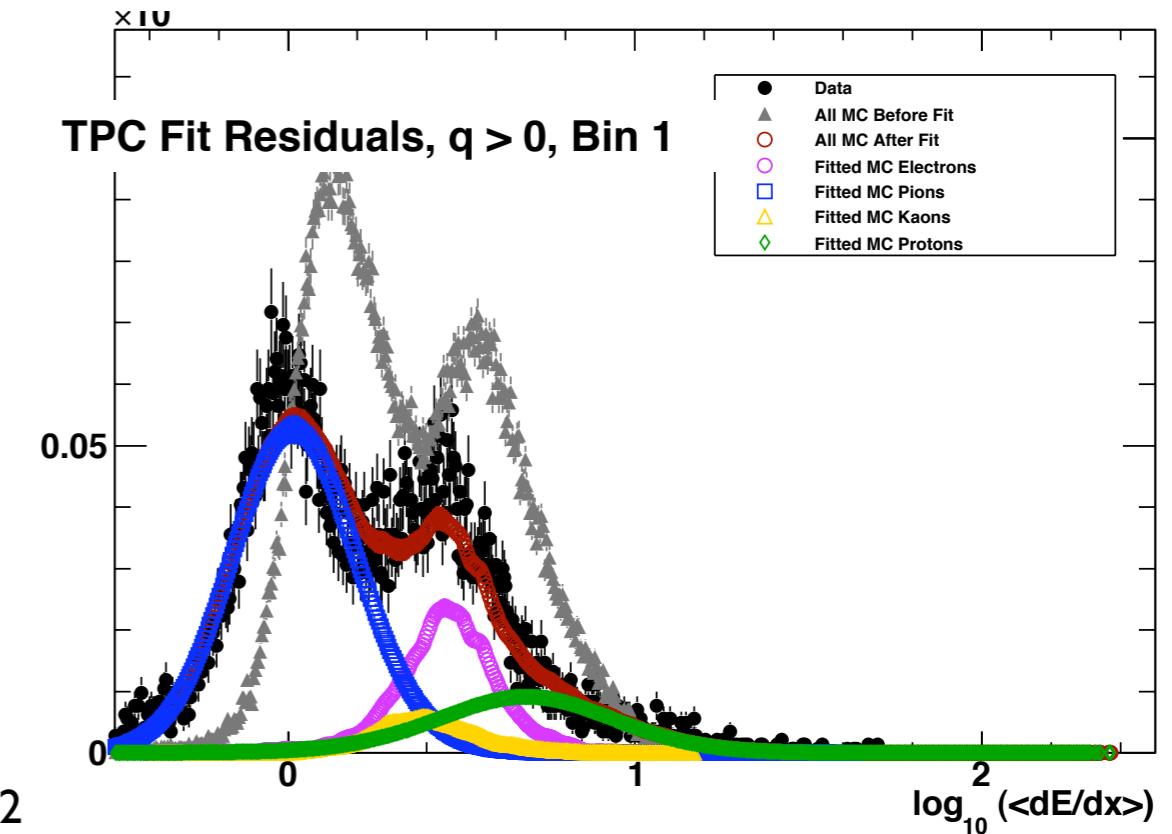
TPC  $\log_{10}(\langle dE/dx \rangle)$ ,  $q > 0$ , Bin 4 (0.30,0.25)-(0.40,0.33)



TPC  $\log_{10}(\langle dE/dx \rangle)$ ,  $q > 0$ , Bin 8 (0.40,0.05)-(0.50,0.15)

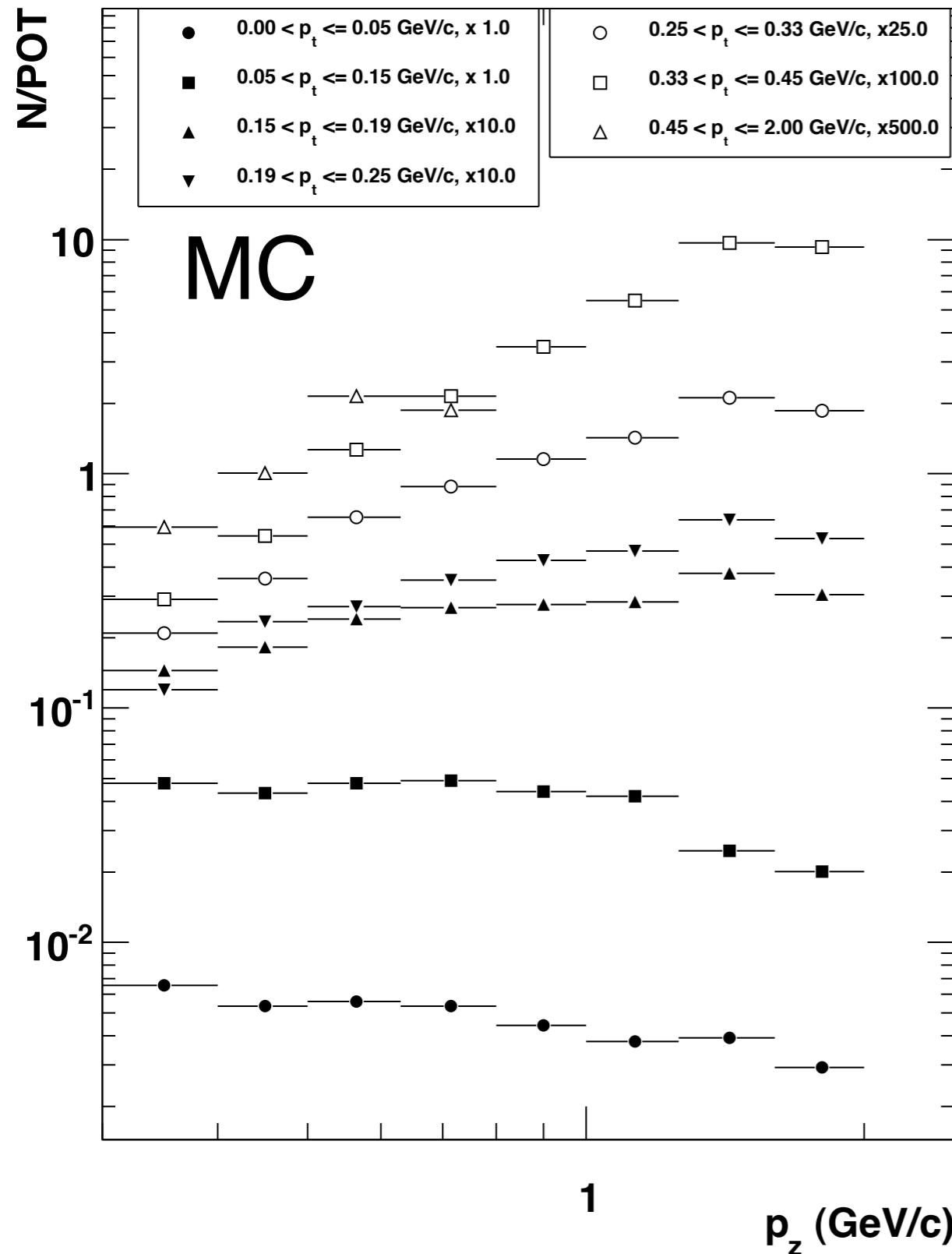


TPC  $\log_{10}(\langle dE/dx \rangle)$ ,  $q > 0$ , Bin 12 (0.40,0.33)-(0.50,0.45)

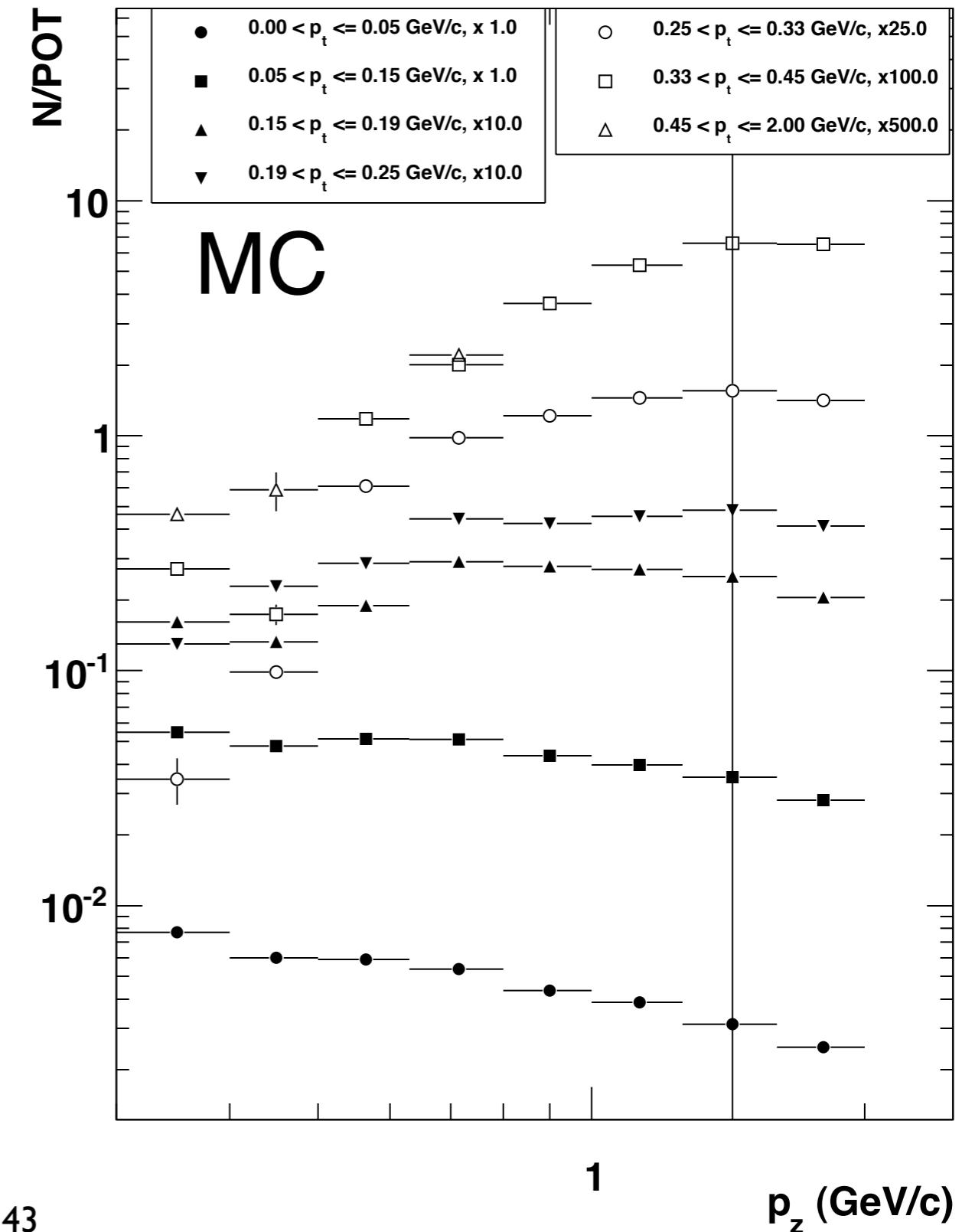


# Preliminary Pion Yield Measurement (TPC-only)

$N(\pi^+)/POT$  vs.  $p_z$



$N(\pi^-)/POT$  vs.  $p_z$



# Forward Neutron Production at MIPP Experiment

## analysis status report

T.S. Nigmanov, D. Rajaram, M.J. Longo, H.R. Gustafson  
University of Michigan

MIPP Review, Fermilab  
October 9, 2009

# neutron analysis

## Motivation

- There is only one experiment with neutron production from p+p at 158 GeV/c (NA49)
- HARP reaches only 15 GeV and does not measure neutrons
- MIPP covers variety of targets and beam momenta
- Proton Radiography
- Test, provide input to neutron production in Monte Carlos

## Analysis outline

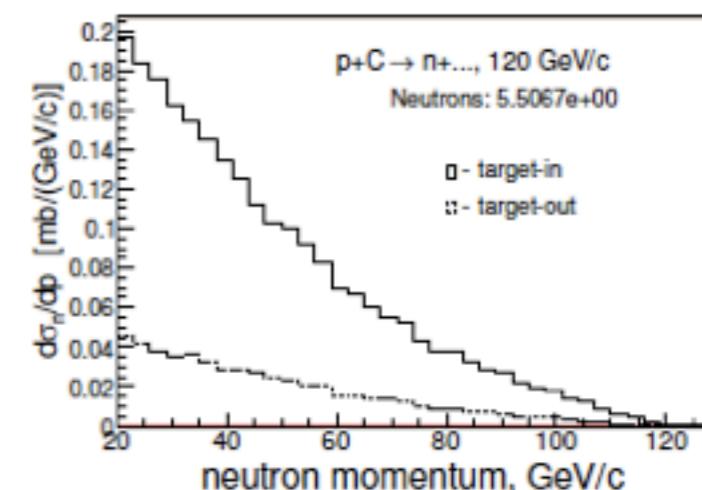
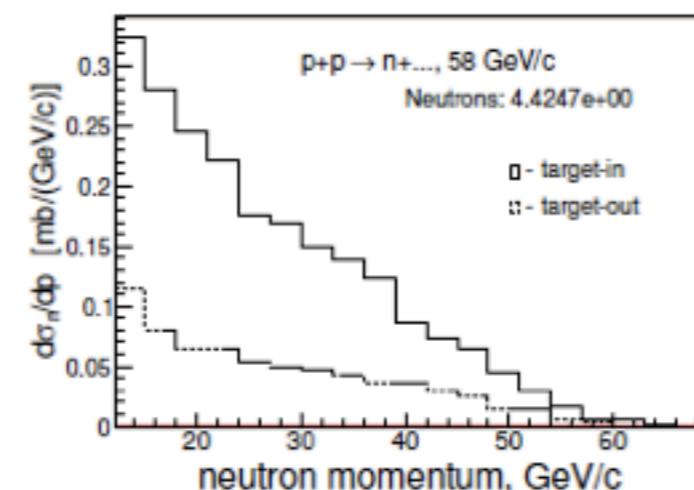
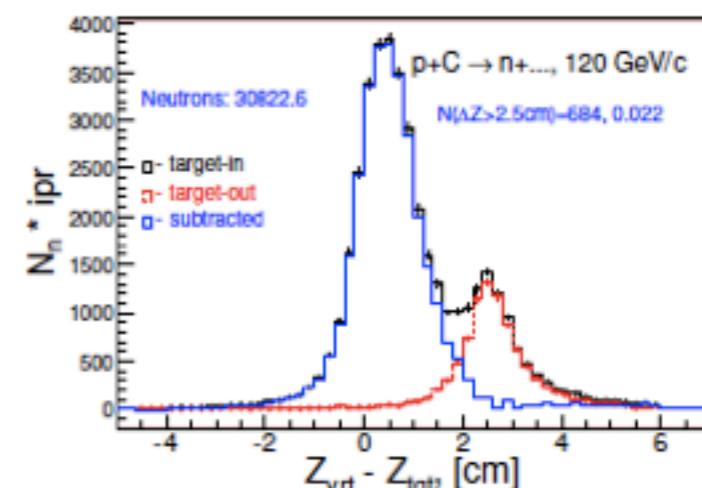
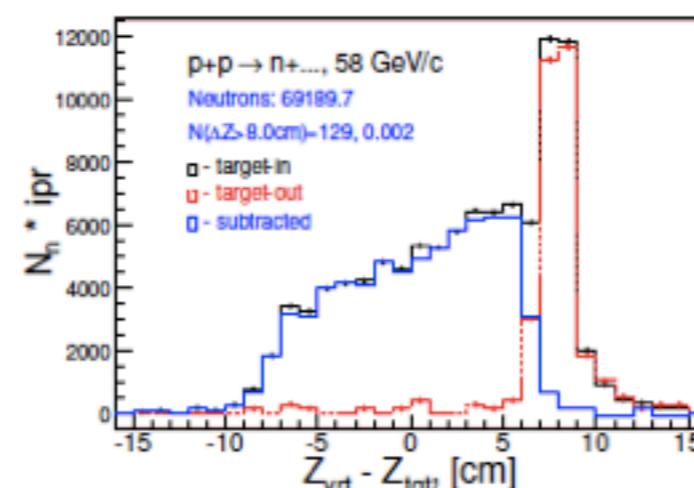
- Event selection (good run, good beam track)
- Neutron selection
- Trigger efficiency
- Acceptance, selection efficiency
- Backgrounds
- Systematic uncertainties (not covered)
- Neutron cross section (preliminary)

## Measured neutron spectra (uncorrected)

$$\sigma_n = \frac{N_n(t_{in}) - N_n(t_{out})}{N_{beam}} \times \frac{1}{A} \times \frac{1}{n_t} \times \frac{1}{bs} \times 10^4, \text{ mb/(GeV/c)}$$

- $E_n = E_{hcal} - E_{trks,hcal}$  (if)
- $p_n(\min) = 12(20)$  GeV/c for  $p_{beam} = 58(120)$  GeV/c
- $\theta_n(\max) \approx 23$  mrad

64155 target, $p_b$	$N_n$	$\sigma_n, \text{ mb}$
H <sub>2</sub> , 58 GeV/c	69190	$4.42 \pm 0.07$
Be, 58 GeV/c	3618	$3.83 \pm 0.25$
C, 58 GeV/c	27363	$3.10 \pm 0.08$
Bi, 58 GeV/c	14749	$0.85 \pm 0.02$
U, 58 GeV/c	25588	$0.70 \pm 0.01$
Be, 120 GeV/c	53087	$6.25 \pm 0.02$
C, 120 GeV/c	30823	$5.51 \pm 0.03$
Bi, 120 GeV/c	34180	$1.56 \pm 0.01$



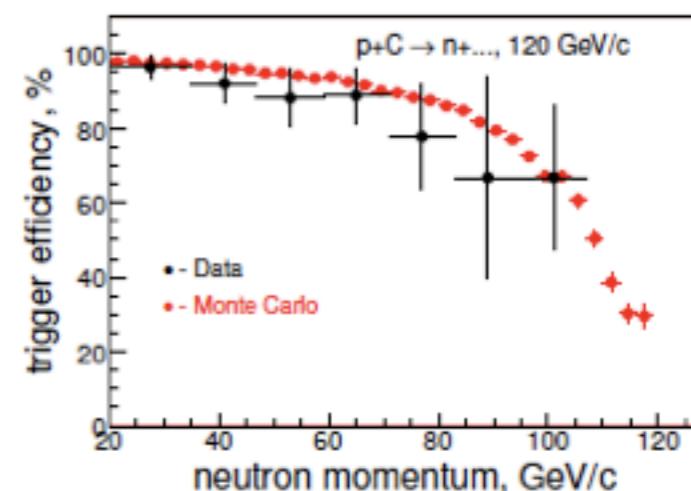
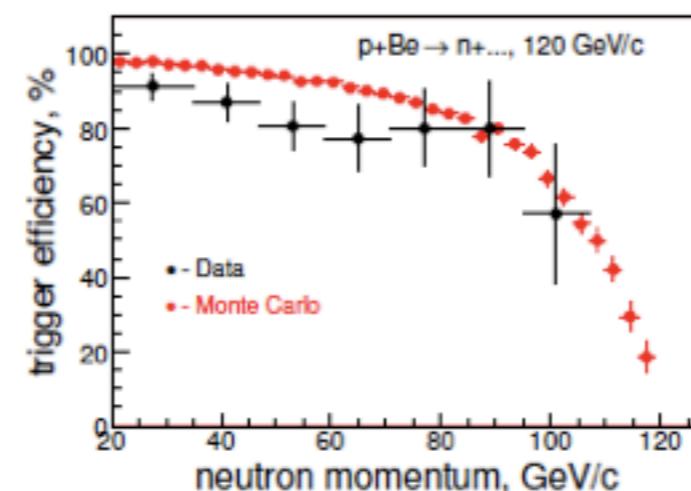
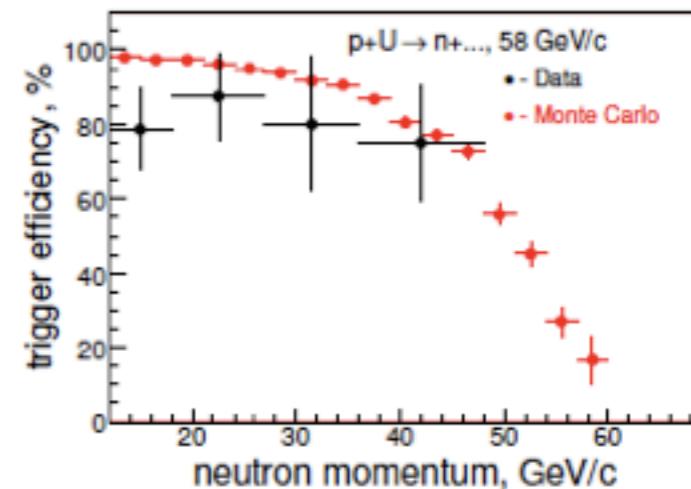
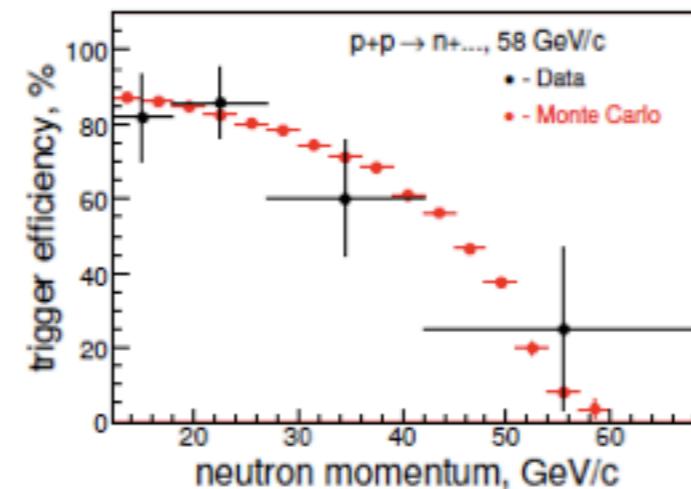
Top: the interaction vertex positions for H<sub>2</sub> (left) and C (right) targets.  
Bottom: the uncorrected cross section  $d\sigma_n/dp$  as a function of the neutron momentum for H<sub>2</sub> (left) and C (right) targets.

## Trigger efficiency

- Use unbiased beam triggers
- Select neutrons
- See if trigger fires

target, $p_b$	$\epsilon_{trig}$ (data)	$\epsilon_{trig}$ (mc)
H <sub>2</sub> , 58 GeV/c	0.72±0.07	0.75
Be, 58 GeV/c	1.00±?	0.82
C, 58 GeV/c	0.80±0.18	0.85
Bi, 58 GeV/c	0.57±0.19	0.91
U, 58 GeV/c	0.80±0.07	0.91
Be, 120 GeV/c	0.84±0.03	0.92
C, 120 GeV/c	0.89±0.03	0.93
Bi, 120 GeV/c	0.76±0.03	0.97

MC results are based on FLUKA and GEANT simulation.



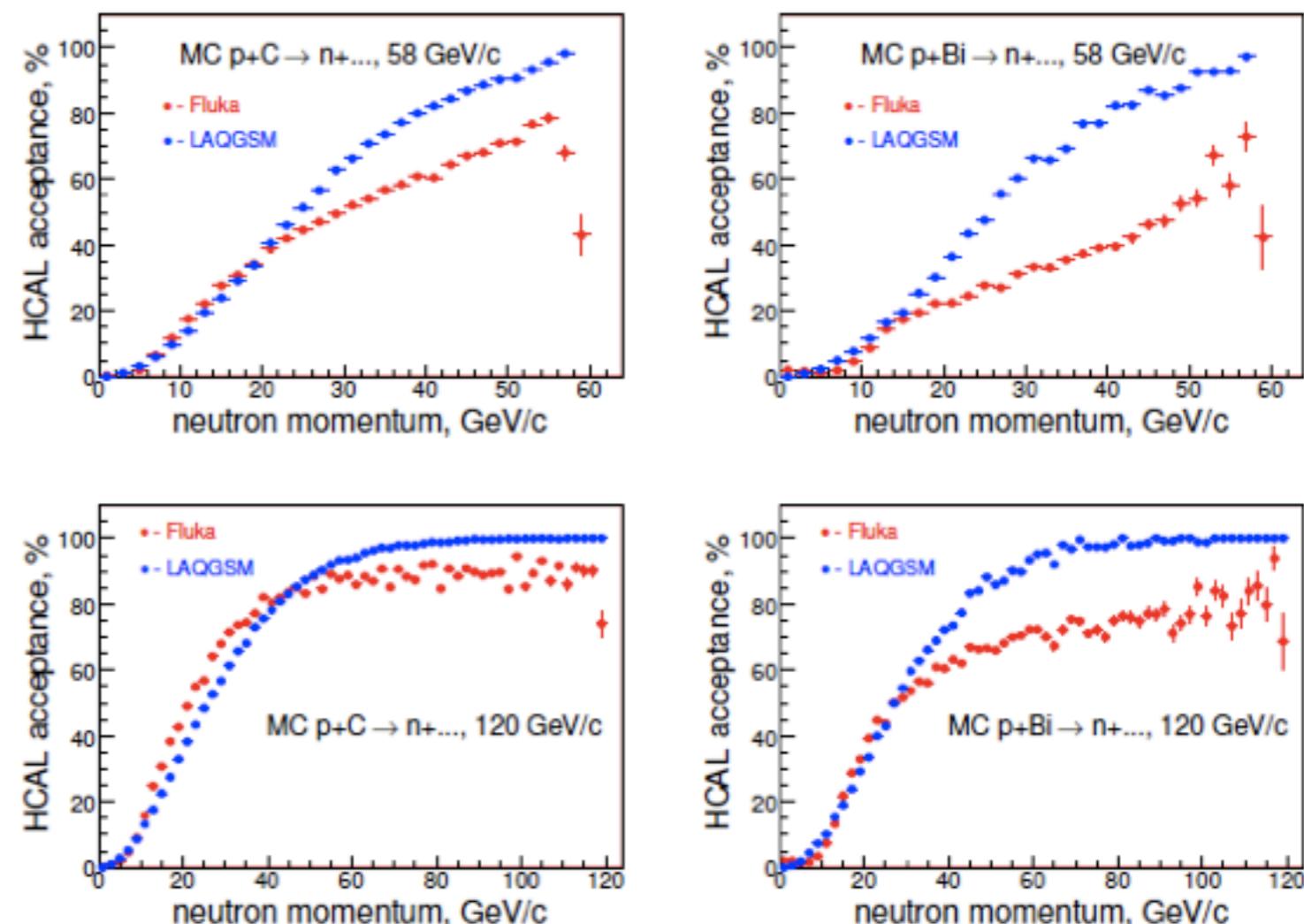
Top: the trigger efficiency as a function of the neutron momentum for H<sub>2</sub> (left) and U (right) targets.

Bottom: the trigger efficiency as the function of the neutron momentum for Be (left) and C (right) targets.

## Calorimeter acceptance, total cut efficiency

- Use MC simulation, trigger is on
- $a_{hcal} = N_n(hcal) / N_n(gen)$
- $\epsilon_{nsel} = a_{hcal} \times \epsilon_{n-reco}$

target, $p_b$	$a_{hcal}$	$\epsilon_{nsel}$
H <sub>2</sub> , 58 GeV/c	0.51	0.43
Be, 58 GeV/c	0.46	0.39
C, 58 GeV/c	0.44	0.37
Bi, 58 GeV/c	0.26	0.22
U, 58 GeV/c	0.26	0.22
Be, 120 GeV/c	0.81	0.71
C, 120 GeV/c	0.79	0.71
Bi, 120 GeV/c	0.61	0.55



Top: the calorimeter acceptance as a function of the neutron momentum for C (left) and Bi (right) targets at 58 GeV/c beam momentum.

Bottom: the calorimeter acceptance as a function of the neutron momentum for C (left) and Bi (right) targets at 120 GeV/c beam momentum.

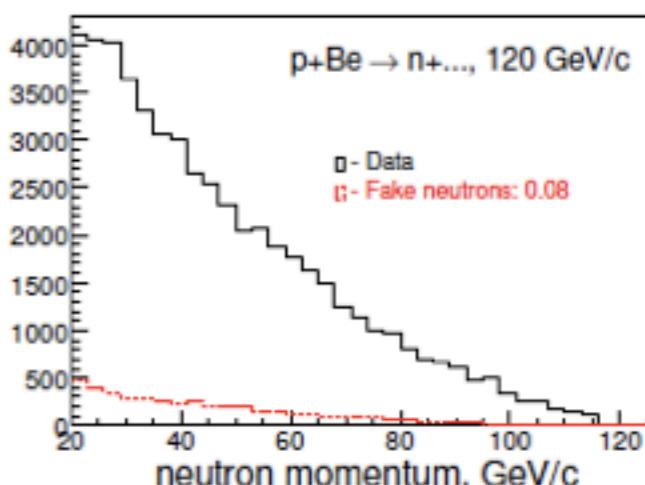
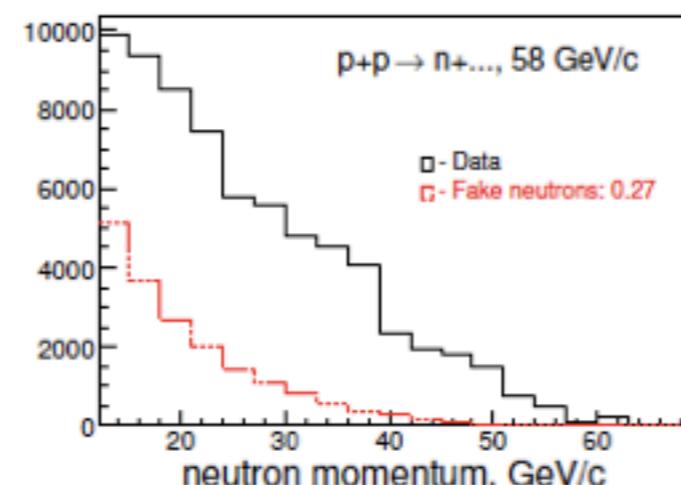
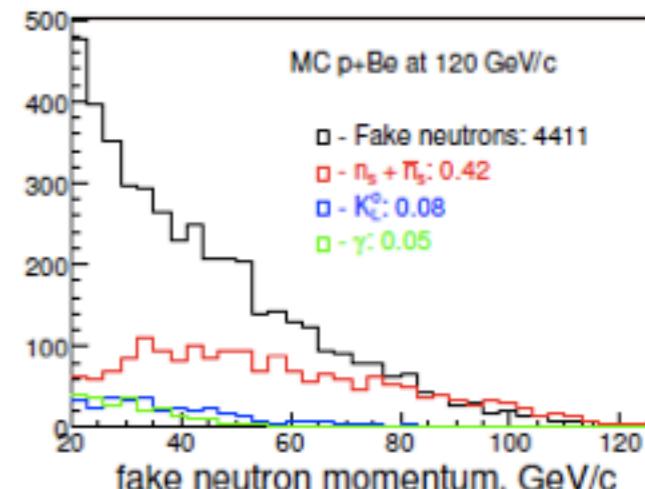
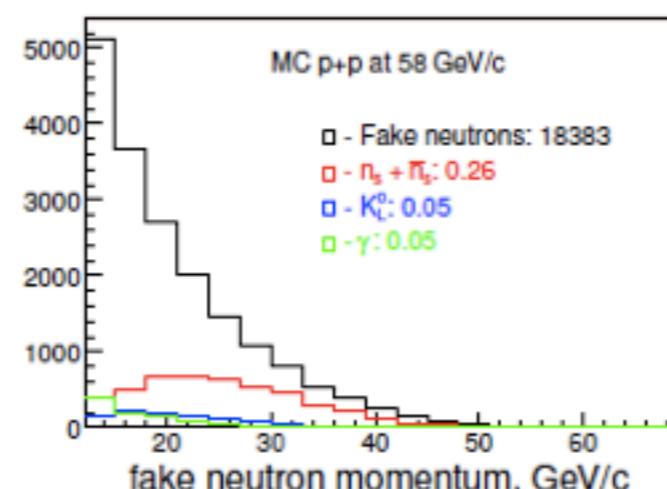
NOTE: Studies with LAQGSM approach are in progress.

## Backgrounds

Sources: un/mis-reconstructed tracks and neutrals:  $K_L^0, n_s, \gamma$

- Use MC events with no neutrons
- Select neutrons same way as in data
- What will pass is the background
- Apply normalization

target, $p_b$	Backgr.	Fraction
H <sub>2</sub> , 58 GeV/c	18383	0.27
Be, 58 GeV/c	271	0.07
C, 58 GeV/c	2038	0.07
Bi, 58 GeV/c	676	0.05
U, 58 GeV/c	1594	0.06
Be, 120 GeV/c	4411	0.08
C, 120 GeV/c	2223	0.07
Bi, 120 GeV/c	2014	0.06



Top: the background spectrum with the neutrals superimposed for  $H_2$  (left) and Be (right) targets.

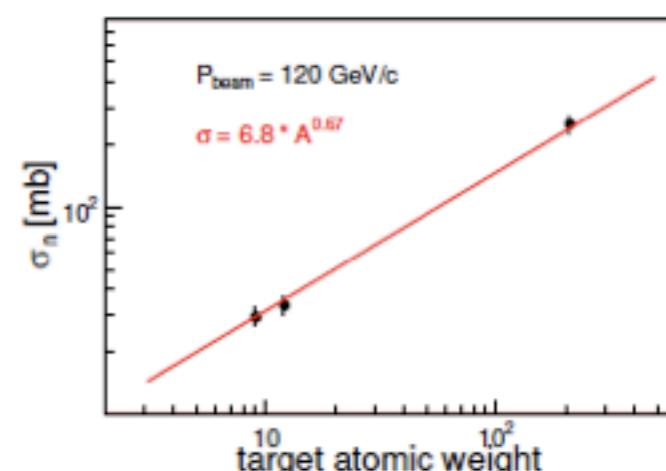
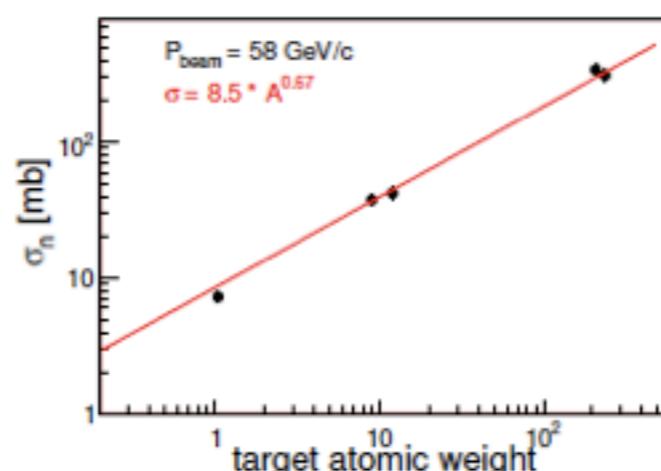
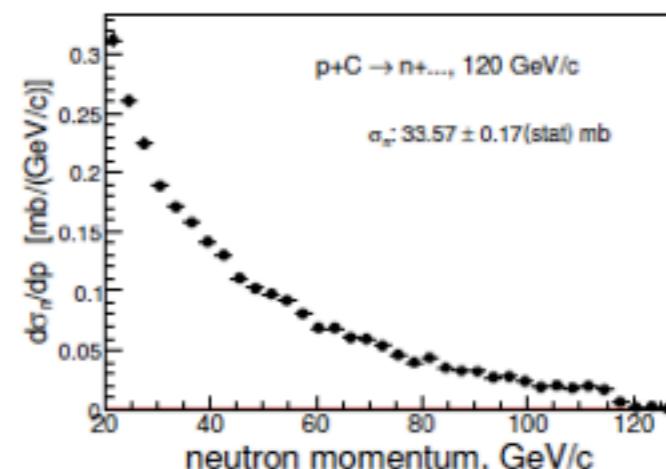
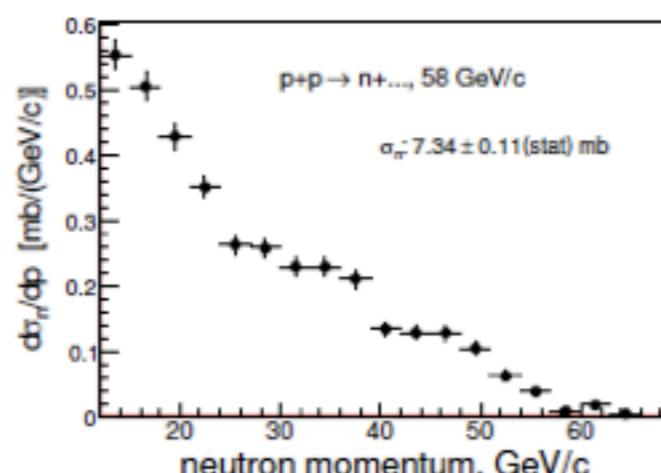
Bottom: the neutron spectrum (data) with the total background superimposed for  $H_2$  (left) and Be (right) targets.

Results are based on FLUKA and GEANT simulation.

## Neutron cross section results (preliminary)

$$\sigma_n = \frac{N_n(t_{in}) - N_n(t_{out}) - N_n(\text{backgr})}{N_{\text{beam}} \times \epsilon_{\text{trig}} \times \epsilon_{\text{nsel}}} \times \frac{1}{A} \times \frac{1}{n_t} \times \frac{1}{bs} \times 10^4, \text{ mb}/(\text{GeV}/c)$$

target, $p_b$	$\sigma_n$ , mb
H <sub>2</sub> , 58 GeV/c	$7.3 \pm 0.1$
Be, 58 GeV/c	$37.7 \pm 2.4$
C, 58 GeV/c	$42.3 \pm 1.1$
Bi, 58 GeV/c	$341.4 \pm 8.4$
U, 58 GeV/c	$311.3 \pm 4.6$
Be, 120 GeV/c	$29.4 \pm 0.1$
C, 120 GeV/c	$33.6 \pm 0.2$
Bi, 120 GeV/c	$251.0 \pm 1.0$



Top: the resulting  $d\sigma_n/dp$  for H<sub>2</sub> (left) and C (right) targets.

Bottom: the resulting  $\sigma_n$  as a function of target atomic weight for 58 GeV/c (left) and 120 GeV/c (right) beam momentum, respectively.

# Back-up plots

## neutron production (within HCAL): Fluka vs LAQGSM

